Missouri River – Fort Peck Dam to Ponca State Park Geomorphological Assessment Related to Bank Stabilization

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December 2001

PREFACE

This report discusses work performed during Fiscal Years 1999 through 2001 by the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Corps of Engineers Engineer Research Development Center (ERDC), requested and sponsored by the U.S. Army Corps of Engineers Omaha District.

The report was prepared under the direct supervision of Dr. Yen-Hsi Chu, past Chief, River Sedimentation Branch, and Mr. James R. Leech current Chief, River Sedimentation Branch, and under the general supervision of Mr. Thomas W. Richardson, Director of CHL. The report was prepared by Drs. David S. Biedenharn, Rebecca S. Soileau, Lisa C. Hubbard and Mrs. Peggy H. Hoffman (ERDC), Dr. Colin R. Thorne and Chris C. Bromley (University of Nottingham), and Dr. Chester C. Watson (Colorado State University).

At the time of publication of this report, Dr. James R. Houston was Director of ERDC and Colonel John W. Morris III was Commander.

EXECUTIVE SUMMARY

The overall objective of this study was to evaluate the potential impacts of bank stabilization on the morphologic processes in the Missouri River with a particular emphasis on the formation and persistence of habitat bars. This investigation addresses the following four open water reaches of the Missouri: (1) Fort Peck Dam to vicinity of Yellowstone River (304 kilometers); (2) Garrison Dam to Lake Oahe (127 kilometers); (3) Fort Randall Dam to the Niobrara River (58 kilometers); and (4) Gavins Point Dam to Ponca (93 kilometers). This report provides an additional tool for designers and managers to use when developing and assessing bank stabilization projects.

A detailed geomorphic, hydrologic, and sediment transport analysis of each study reach was conducted. A total of 655 sediment samples from the banks, bed, bars, islands and tributaries were collected and analyzed. The percent of the bank material greater than the bed material size for each reach ranged from about 21% in the Fort Randall Reach to 60% in the Garrison Reach with the Fort Peck and Gavins Point Reaches both being about 48%. Each study reach was divided into individual Geomorphic Reaches (GR), and a sediment budget was calculated for each GR as well as for the entire study reach. The sediment budget was calculated using comparison of historical aerial photography and cross-sectional data from the late 1960s to 1998. From the sediment budget, the percent of the total bed material load comprised of material supplied from the banks was calculated. The percent bank contribution varied considerably from GR to GR, ranging from as low as 3% to as high as 58%. The overall study reach bank contribution percentages are: (1) Fort Peck Reach – 17%; (2) Garrison Reach – 13%; (3) Fort Randall Reach – 8%; and (4) Gavins Point Reach – 24%. Tables are provided that show the percent reduction in bank material supply resulting from various stabilization schemes ranging from stabilizing 10%, 20%, etc. up to 100% of the eroding areas for each GR.

The supply of sediment from the banks is only one factor that affects bar morphology. The three primary factors, identified in this study, necessary for the formation and persistence of bars are a supply of suitably sized sediment, a local channel geometry (channel width) and a stability status (aggradation, degradation, or equilibrium) that allows and promotes bar existence. In a system such as the Missouri River, where there is an abundant supply of material, the local geometry is probably the dominant factor with respect to bar morphology. As a consequence, when considering the potential impacts of a proposed bank stabilization scheme, the investigator can not just focus on one factor, but rather must consider a number of factors. Each bank stabilization project should be evaluated on a case by case basis in an engineering-geomorphic investigation that identifies and quantifies the impacts of channel width, reduction in sediment supply, and existing stability of the reach. Guidance for the evaluation of these factors is provided.

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CONVERSION FACTORS
SI TO NON-SI UNITS OF MEASUREMENT

SI (metric) units of measurement used in this report can be converted to Non-SI units as follows:

Multiply	By	To Obtain
centimeters	0.39	inches
meters	3.28	feet
kilometers	0.6	miles
kilometers/hour	0.5396	knots
cubic meters	35.3	cubic feet
cubic meters	1.3	cubic yards
hectares (ha)	2.5	acres

ABBREVIATIONS

ASCII	=	American Standard Code for Information Interchange
cm	=	centimeter
CIR	=	color-infrared
CMS	=	cubic meters per second
EIS	=	Environmental Impact Statement
ERDC	=	Engineer Research and Development Center
ERDC-EL	=	Engineer Research and Development Center-Environmental Lab
ft	=	feet
FWS	=	Fish and Wildlife Service
GIS	=	Geographic Information System
GR	=	Geomorphic Reaches
GPS	=	Global Positioning System
HB	=	Habitat Bar
ha	=	hectar
hr	=	hour
HEC-DSS	=	Hydrologic Engineering Center's Data Storage System
HEC-RAS	=	Hydrologic Engineering Center's River Analysis System
IDAS	=	Image Data Acquisition Systems
km	=	kilometer
m	=	meters
mi	=	mile
RM	=	river mile
sq	=	square
SVHS	=	Super-VHS
USACE	=	U.S. Army Corps of Engineers
USAEDNMRR	=	U.S. Army Engineer Division, Northwestern, Missouri River Region
USGS	=	U.S. Geological Survey
WSEL	=	water surface elevation
WES	=	Waterways Experiment Station
WPT	=	waypoint
w:d	=	width:depth

CHAPTER 1

BACKGROUND

Section 33 of the Water Resources Development Act of 1988 authorized the U.S. Corps of Engineers (USACE) to alleviate bank erosion and related problems along the Missouri River from Fort Peck Dam, Montana to Ponca State Park, Nebraska. The act stated that both structural and non-structural measures could be used to accomplish this. The projects constructed under this authority, as well as other non-Federal stabilization efforts along the river, have created concern about the overall cumulative impacts of bank stabilization on fish and wildlife resources along the upper Missouri River. The Omaha District is conducting environmental impact studies for the Section 33 Program. A principal component of these studies is the determination of the geomorphic impacts of the stabilization program on habitat within the system.

CHAPTER 2

OBJECTIVES OF THE STUDY

The overall objective of this study was to evaluate the potential impacts of bank stabilization on the morphologic processes in the Missouri River with a particular emphasis on the formation and persistence of non-vegetated sandbars. The geographic and subject limits of this study were set through a series of public scoping meetings held at various locations along the study reach in the spring and summer of 1999. This investigation addresses the four open water reaches of the Missouri River, totaling approximately 560 kilometers (km) in Montana, North Dakota, South Dakota, and Nebraska. The four study reaches with approximate reach lengths include:

(1) Fort Peck Dam to vicinity of Yellowstone River (304 km);
(2) Garrison Dam to Lake Oahe (127 km);
(3) Fort Randall Dam to the Niobrara River (58 km); and
(4) Gavins Point Dam to Ponca (93 km).

The reader shall keep in mind that there are a number of factors that influence a river's alluvial processes, and that bank stabilization can impact features other than bars and islands. This report is intended to provide an additional tool for designers and managers to use when developing and assessing bank stabilization projects. The report is also intended to support related studies such as Programmatic EIS and Section 10/404 permits.

CHAPTER 3

LITERATURE REVIEW

3.1. The Effect of Dams

Channel response to flow regulation may vary considerably depending upon the purpose and manner of operation of the dam. Construction of a dam has a direct impact on the downstream flow and sediment regime. Channel adjustments to the altered flow duration and sediment loads include changes in the bed material (armoring), bed elevation, channel width, planform, and vegetation. The reduction in the discharge and sediment load, as might be expected downstream of a dam, tends to produce counter-acting results. Bed scour (degradation) would normally be anticipated with a decreased sediment supply, while reducing the discharge might tend to create an aggradational tendency. Consequently, the response of a channel system to dam construction is extremely complex. The specific channel response will depend upon the magnitude of changes in the flow duration and sediment loads and the existing channel regime downstream of the dam. Therefore, channel response downstream of a dam is very complex and may vary from stream to stream. Generally, the initial response downstream of a dam is degradation of the channel bed close to the dam and sedimentation further downstream due to increased supply from the degrading reach. This is the typical response most commonly anticipated downstream of a dam. Degradation may migrate downstream with time, but generally it is most significant during the first few years following closure of the dam. In some situations, a channel may shift from a degradational to an aggradational phase in response to slope flattening due to degradation, increased sediment inputs from tributaries and bed and bank erosion, and reduction in the dominant discharge.

Although it is not possible to accurately predict precisely how a river system will respond to the presence of a dam due to the complex nature of the interactions involved (Watson *et al.* 1999), a considerable number of reports detailing the changes that have occurred in the four study reaches of the Upper Missouri River have been written or commissioned by the USACE. Some, such as McCombs-Knutson Associates (1984); River Pro's (1985, 1986); Darby and Thorne (1996); HDR Engineering (1998); and Simons *et al.* (1999) looked at bank erosion issues, while Pokrefke *et al.* (1998) undertook a more wide ranging assessment of channel degradation in response to the presence of the dams, and the implications of these effects for a change in operating regime of the four dams. Other reports examined the changing downstream trends in channel variables such as bed material grain size distributions, average bed elevations, thalweg elevations, water surface profiles, stage trends, and channel geometry, in order to elucidate the impact of each of the dams (USACE 1986; Dangberg *et al.* 1988a, 1988b; U.S. Army Engineer Division, Northwestern, Missouri River Region (USAEDNMRR) 1994; Midwest International, Inc. 1997).

One of the few reports that tried to predict future channel changes is that of WEST Consultants Inc. (1998). Using HEC-2 and HEC-6 modeling, they project average bed elevations and water surface elevations for the Fort Randall Reach from 1995 to 2045 under low-, medium-, and high-flow scenarios. The results show that degradation continues to occur immediately downstream of the dam while aggradation continues in the area around the Niobrara River confluence. Both the degradation and the aggradation are most intensive under the high-flow scenario. The aggradation at the downstream end of this reach is largely a function of the delta that has formed at the confluence of the Missouri and Niobrara Rivers, due to the Missouri's inability to remove all the sediment deposited by the Niobrara. Because of the problems caused by this excessive aggradation, the areas upstream and downstream of the delta along the Missouri River and also upstream along the Niobrara River have been extensively studied (Resource Consultants and Engineers 1992, 1993; USACE 1994b).

3.2. Mid-channel Bars and Islands

There is a large body of literature relating to mid-channel bars and islands, much of which is in relation to gravel-bed, braided rivers (e.g., Smith 1974; Hein and Walker 1977; Ashmore 1982, 1991, 1993; Church and Jones 1982; Fujita 1989; Brierley 1991; Bridge 1993). Nevertheless, it is still relevant to this study, despite the Upper Missouri having a straight to meandering planform and having a high proportion of sand in its bed and banks. Hooke (1986), in her study of the meandering River Dane, whose sedimentology ranges from sand to cobbles, states that despite the channel not being truly braided the development and sedimentology of the medial bars is comparable to that of individual braid bars. Germanoski and Schumm (1993) note that observations of bar-forming processes in sand and gravel-bed channels indicate that both form and processes in the flume and in natural braided rivers, of wide-ranging sizes, are kinematically and geometrically similar.

One of the classic papers on the development of a central channel bar is that of Leopold and Wolman (1957). Based on observations of both natural rivers and flume studies they found that initially, a short submerged central bar is deposited during a high flow. The head of the bar is composed of the coarse fraction of the bedload that is caused to accumulate by some local condition. As the water depth over the bar decreases the velocity stays the same or increases and this leads to finer particles moving over the top of the bar and depositing on its downstream end. Once the bar has reached a certain size the anabranches become unstable and begin to cut laterally into the riverbank. The anabranches also deepen and this may cause the bar to emerge as a subaerial bar or island. The above process may repeat itself in the anabranches and thus lead to the development of a braided pattern. As flow velocities decrease on the insides of the original anabranches the bar may grow laterally. If and when vegetation becomes established on the exposed bar, this will promote more deposition of fines and, in turn, development of more vegetation. Ultimately this leads to the development of a stable island. Coleman (1969) identified a very similar process of braid bar development in the Brahmaputra River, while Thorne *et al.* (1993) state that islands in the Brahmaputra are built by the amalgamation of groups of braid bars. This latter observation is supported by the flume work of Germanoski and Schumm (1993), who showed that braid bar size increases in degrading gravel-bed streams due to incision of the main channel, the drying out of the smaller anabranches between the braid bars and the subsequent coalescence of these bars.

Lane (1995) provided a more wide-ranging consideration of bar development in a braided system and identified five mechanisms, which are not mutually exclusive, of formation. The first, the deposition of a central bar, is as described by Leopold and Wolman, but Lane goes one step further and states that deposition is induced at the local scale by one or a combination of decreasing discharge, increased upstream sediment inputs and variations in channel geometry. Reach-scale variations in channel geometry can also result in the second method of formation of a central braid bar: a transverse bar conversion. When the ratio of water depth to D_{90} is greater than 2-3, the pools at sites of flow convergence are likely to scour. If flow divergence, and therefore velocity reduction, occurs further downstream then some of the scoured material may be deposited as a lobe, which can trap further bedload and grow to a sufficient size to initiate bank erosion. These are both examples of depositional bar building processes. A key erosional process is chute cutoff, which requires a pre-existing set of one or more alternate bars. When flow is diverted across one of these bars, the sudden increase in velocity as it moves off the end of the bar can increase the value of bed shear stress to above its critical value, which causes headward incision. Eventually this completely separates the bar from the bank. Multiple dissections of a lobe are caused either by a highly sediment deficient flow moving over the bar, or the erosion of a previously aggraded bar head by a low flow which can still generate sufficient shear stress to do so. The final mechanism of bar formation is avulsion. This can be triggered by ponding behind a bar head, bank erosion in curved anabranches or aggradation and eventual blocking of a single anabranch.

Ashworth (1996) conducted a series of flume studies to investigate the formation of mid-channel bars immediately downstream from the junction between two tributary channels. He proposed the following five-stage model for bar development: (1) development of confluence scour with flow convergence and maximum velocity in the channel center; (2) exceedance of the local transport capacity and initial stalling of coarse sediment in the channel thalweg downstream of the scour; (3) bar growth through entrapment of all sizes of bedload; (4) change from velocity maximum to minimum and flow convergence to divergence when the bar height is between 40% and 60% of the thalweg depth, but with a mean of around 55%; (5) broadening of the bar top platform, a drop in local competence and bankwards migration of the two distributaries whose cross section and velocity remains approximately constant.

Despite all the research that has been undertaken into the development of the mid-channel bar/braided stream pattern, two key areas of uncertainty still remain. First, what initiates bar deposition and, secondly, what is the source of the material that builds the bars? Various suggestions have been put forward to answer the first point. Leopold and Wolman (1957) simply stated that the coarse fraction of the bedload was deposited in mid-channel at a location where the local flow competence was insufficient to transport it. Ashmore (1991, 1993) suggested that the initial deposition of material is due to the slowing down of a thin bedload sheet, possibly only one grain thick, which has been transported downstream as a discrete morphological unit. Ashworth (1996), on the other hand, considers local exceedance of the transport capacity and sediment accumulation in the channel center by strongly convergent flows, to be a more likely cause of the initial deposition. In his flume experiments, exceedance of the transport capacity was caused by a rapid increase in sediment supply from scour at the junction between two artificially stabilized tributary channels at the head of the flume. Both Ashworth (1996) and Davoren and Mosley (1986) consider this confluence-diffluence unit to be of fundamental importance in the building of a mid-channel bar. Hooke (1986), in her work on the River Dane, stated that the initial deposition is of coarse material on a riffle and may be caused by reversals of velocity and shear stress in pools and riffles as flows increase.

The second question is equally problematical to answer. The only papers uncovered for this study that links the sediments within a mid-channel bar directly to their source are those of Xu (1996, 1997). In his study of the middle Hanjiang River, a sand-bed, unstable, braided channel with a width:depth ratio of 209 to 239, he identified 20 minerals found in sediment samples from the channel. He then plotted the percentage of each mineral found in the mid-channel bar material against the percentage found in the three possible sources: the banks, the bed of the Hanjiang River upstream of the bars, and an upstream tributary, and found that the banks supplied the majority of the bar materials. The correlation coefficient for the bar-bank plot was 0.94, while those for the bar-bed and bar-tributary plots were 0.89 and 0.51, respectively. Based on these plots, Xu used the following index to determine the degree of importance of each mineral source:

$$I = \sum(M_{s,i} - M_{bar,i})^2 \qquad (3.1)$$

where $M_{bar,i}$ is the percentage of the *i*th mineral in the bars, and $M_{s,i}$ is the percentage of the same mineral in one of the three material sources. The smaller the I value the larger the contribution of the material source to bar formation. As calculated for the bank, the bed of the Hanjiang River, and the tributary, the I values are 73.83, 336.37, and 984.58, respectively, thus showing even more conclusively that bank material is the major source of material for mid-channel bar building in the Hanjiang River. Although these results appear conclusive for the middle Hanjiang River, the important question to ask is to what extent are they representative of all other rivers that contain mid-channel bars or a braided planform? Carson and Griffiths (1987), in their work on gravel-bed rivers, state that most braid-bar material comes from bank erosion and bartail trimmings as opposed to bed scour, while Hooke (1986) stated that the major cause of mid-channel bar development on the River Dane is the rapid erosion of low resistance banks in steep sections and in bends. She goes on to say that mid-channel depositions from other causes, e.g., tributary inputs or due to a channel obstruction, can usually be identified due to differences in bar morphology, sedimentology, and development sequence. Other than these papers, however, no further reference to this issue has been found in the literature.

A further question that arises from the previous two, and for which no specific mention has been found in the literature, relates to the source of the material that is deposited at the very beginning of bar development. The flume studies of Ashworth (1996) imply strongly that the initial deposition of material downstream of the confluence of the two tributaries, is of material scoured from the bed at this confluence. Hooke (1986) also stated that scoured bed material is generally not transported very far downstream from the point of scour before being deposited. If this is the case, and assuming that bank material does provide the bulk of the material in the bar, then the contribution of the scoured bed material is just as important as the bank material in the formation of a mid-channel bar.

3.3. Bank Stabilization and Sediment Supply

One final area of importance to consider for this study, and unfortunately one where literature again appears to be scarce, is the effect that any further bank stabilization measures will have on the sediment supply to the channel and, hence, how this will affect the bar and island morphology. This consideration becomes especially important for the Upper Missouri River if it is established that the bars and islands are composed primarily of material from eroding banks. Pokrefke *et al.* (1998) undertook to predict how any future increases in bank stabilization would affect erosion rates in the four reaches. For the Fort Peck, Garrison, and Fort Randall Reaches they found that an exponential relationship exists between increasing amounts of bank stabilization and decreasing rates of bank erosion, while in the Gavins Point Reach this relationship is linear. In part, this is due to the fact that the first three reaches are much closer to a position of dynamic equilibrium than the Gavins Point Reach and so are stabilizing naturally anyway. In a famous series of laboratory flume experiments, Friedkin (1945) investigated the effects of bank stabilization on a meandering sand channel. In one experiment he stabilized three meander bends in the middle of a meandering section of channel, and observed the development of a mid-channel bar in the crossing after the first unstabilized bend downstream of the three stabilized ones. This indicates that bedload from above the stabilized reach passed straight through the three bends and deposited downstream of them as soon as the hydraulic conditions once again allowed this.

CHAPTER 4

METHODS AND ANALYSIS

4.1. Field Investigations and Data Collection

4.1.1. Data Gathering.

A data gathering effort was conducted to assemble all known data, reports, and other information pertinent to the study. The primary sources were the Omaha District, U.S. Geological Survey (USGS), Fish and Wildlife Service (FWS), and the Waterways Experiment Station (WES).

4.1.2. Field Investigations.

4.1.2.1. Aerial Reconnaissance.

An aerial reconnaissance of the entire study reach was conducted by WES and Omaha District personnel. A geo-referenced video compatible for use with the GIS database was made of all of the reaches by a trained GIS operator from WES. A map of the coverage of the videos and examples of frames showing the time and GPS coordinates were provided to the Omaha District.

4.1.2.2. Initial Boat Reconnaissance.

Following the aerial reconnaissance, a boat trip was made covering all four study reaches. The purpose of this reconnaissance was to provide an initial familiarization with the morphology of the river system. While some data such as bed and bank samples were taken on this trip, the primary emphasis was identifying the dominant morphologic processes, particularly with respect to bank stability and mid-channel bars and islands. The areas of active bank erosion were mapped as well as corresponding bank heights. Examples of failure mechanisms include undercutting, block failures, and landslides were noted. Areas that were not actively eroding due to stress from the river but were sources of sediment due to landslides were noted as well. Bank deposit characteristics and stratigraphy were recorded and a classification of types developed on the spot to roughly map major changes in materials. Classification included such terms as border fill, bluff, and terraces – both post- and possible pre-dam in origin. Classification of the islands and bars related to elevation above the water surface and vegetation types. This information was used to help guide the detailed field data collection efforts. A geo-referenced video compatible for use with the GIS database was made of most of the reaches by a trained GIS operator from WES. The video was made concurrently with the reconnaissance and included footage of both banks from the boat position. Stormy weather shut down the video on sections of the Fort Randall and Fort Peck Reaches.

4.1.2.3. Detailed Field Study.

Six hundred sixty five sediment samples at 312 sites from the banks, bed, bars, and islands were collected by a team from Colorado State University (CSU) headed by Sean McCoy under the direction of Chester Watson. Outstanding field support, equipment and personnel were committed by the USACE from the Omaha and North Dakota offices and the North Dakota USGS. Types of data collected and methods are outlined below. For the purposes of this study, definitions of types of bars and islands are listed in Table 4.1.

Table 4.1 Definitions of types of bars and islands.

Bar:	An offshore ridge or mound of sand or gravel built up to or near the surface of the water by currents in a river. Only bars that were exposed above the surface of the water at the time of reconnaissance and sampling are considered in this study. For the purposes of this report, bars are also typically non-vegetated or sustain only very short vegetation that sprouts between inundation events.
Habitat bars or islands:	A bar or island that was identified by biologists as having habitat value for the Least Terns or Piping Plovers.
Non-habitat bars:	A bar that has not been identified specifically as having habitat value for the Least Terns or Piping Plovers.
Island:	A tract of land surrounded by water. For the purposes of this study, islands are distinguished from bars by having vegetation that is established and survives from year to year such as trees and/or shrubs.

The sample sites were chosen based on criteria such as changes in the river's planform, relationships to tributaries, bank material changes noted in the reconnaissance trips, revetted versus unrevetted areas, and known endangered bird species habitat. An effort was made to select sampling sites that would isolate variables of sediment source such as bed, banks, and tributaries. This proved difficult, especially when trying to define reaches that would be affected by revetment versus those that might not. Still the best reaches possible were sought. The resulting sampling reaches are generally less than 9.65 km in length and were identified in order to isolate and investigate particular bar/island-bank, bar/island-tributary, and bar/island-arroyo grain size relationships.

Table 4.2 shows the locations of the Geomorphic Reaches (GRs), sampling reaches, and the habitat bar and island features. The identification of GRs is discussed in detail in a separate section.

The objective of the data collection for this field exercise was to determine the grain size composition of actively failing banks, bars, and islands so that a relationship between the erosional and depositional sediment could be determined. The field team was provided with

Table 4.2 Location of geomorphic reaches, sampling reaches, and habitat bars and islands.

Reach	Geomorphic Reach (1960 RM)	Sampling Reach (1960 RM)	Habitat bar/island (1960 RM)
Fort Peck Reach	GR 1 (1766-1750)	1 (1761.65-1753)	
	GR 2 (1750-1713)	2 (1741.05-1737.7) 3 (1730.8-1725)	
	GR 3 (1713-1700)	4 (1712.9-1711.8) 5 (1707.3-1703.4)	1712.5 (WPT 303)
	GR 4 (1700-1686)	6 (1695.95-1692.7)	1695.9 (WPT 187)
	GR 5 (1686-1654)	7 (1681.4-1679.9) 8 (1679.15-1674.3) 9 (1663-1658.7)	1685.4 (WPT 197) 1674.6 (WPT 211) 1659.1 (WPT 227)
	GR 6 (1654-1621.7)	10 (1651.2-1648.6) 11 (1646.1-1643.2) 12 (1631.2-1627.5)	
	GR 7 (1621.7-1605)	13 (1618.1-1614.3) 14 (1608-1604.2)	1615.3 (WPT 167)
	GR 8 (1605-1582)	15 (1598.35-1594.4)	1595.1 (WPT 178)
Garrison Reach	GR 1 (1390-1376)	1 (1381.2-1376.2)	1380 (WPT 97)
	GR 2 (1376-1363)	2 (1376.1-1373.1) 3 (1371.4-1366.4)	1370 (WPT 112) 1369.1 (WPT 114)
	GR 3 (1363-1353)	4 (1362.65-1359.5)	1361.5 (WPT 121) 1361.1 (WPT 122)
	GR 4 (1353-1340)	5 (1351.5-1346.7)	1348 (WPT 85)
	GR 5 (1340-1324.5)	6 (1335-1329.1)	1334.2 (WPT 132)
	GR 6 (1324.5-1311)	7 (1320-1315.7)	1319.5 (WPT 143)
Fort Randall Reach	GR 1 (880-873.9)	1 (876.7-873.85)	
	GR 2 (873.9-867.5)		
	GR 3 (867.5-861.7)	2 (867.6-864.5)	866.7 (WPT 70) 864.8 (WPT 69)
	GR 4 (861.7-854.5)	3 (858.5-854.5)	
	GR 5 (854.5-851)	4 (854.1-850.95)	851.5 (WPT 556)
	GR 6 (851-844)	5 (847.45-846)	
		6 (843.1-841)	
Gavins Point Reach	GR 1 (811-796)	1 (804.8-800.5) 2 (800.3-793)	804.5 (WPT 6)
	GR 2 (796-776.2)	2 (800.3-793) 3 (782.8-779.3) 4 (779.3-775.7)	803.4 (WPT 7) 797 (WPT 16) 781.7 (WPT 25)
	GR 3 (776.2-764.7)	4 (779.3-775.7) 5 (776-763.4)	
	GR 4 (764.7-753.9)	5 (776-763.4)	

aerial mosaic maps of the four river reaches with sampling sites delineated based on the boat reconnaissance trip and data from the literature. Each sample site was designated as a 'waypoint' (WPT) in the sediment and GPS logs and most were photographed. A GPS unit was used to record the location of each waypoint and downloaded as an ASCII file. Each waypoint was also marked on aerial mosaics in the field. The photographs of the waypoints and photolog in spreadsheet form were given to the Omaha District as was the ASCII files containing the GPS coordinates of each waypoint. Table 4.3 lists the waypoints, their corresponding closest river mile (RM), and a brief description of the sample location.

Table 4.3 Waypoints, their corresponding closest river mile, and a brief description of the sample location.

FORT PECK DAM to YELLOWSTONE RIVER								
WPT	RM	Location	WPT	RM	Location	WPT	RM	Location
148	1626.6	RB	203	1680.2	Island	258	1758.3	Island
149	1626.8	RB	204	1679.9	RB	259	1757.1	Arroyo
150	1627.6	Island	205	1679	Trib	260	1755.3	Island
151	1627.9	Island	206	1678.9	Island	261	1754.8	Bar
152	1628.7	LB	207	1678.1	Bar	262	1754.2	RB
153	1628.9	LB	208	1676.9	LB	263	1753.5	Island
154	1629.4	RB	209	1676.6	LB	264	1753.2	RB
155	1629.7	RB	210	1675.5	Island	265	1751	LB
156	1630.4	Trib	211	1674.7	Island	266	1750.2	LB
157	1630.7	Island	212	1674.6	RB	267	1749.5	LB
158	1630.7	RB	213	1671.5	LB	268	1749	LB
159	1622	RB	214	1668.5	Arroyo	269	1747.3	Trib
160	1621.4	RB	215	1668.4	RB	270	1746.5	RB
161	1619.6	LB	216	1667.6	RB	271	1745.9	RB
162	1619.2	LB	217	1666.3	LB	272	1744.4	RB
163	1617.1	Island	218	1665.8	LB	273	1740.9	RB
164	1616.3	RB	219	1663.7	LB	274	1740.2	RB
165	1616.1	Bar	220	1662.9	Island	275	1740.1	Island
166	1615.5	RB	221	1662.6	Island	276	1739.7	Island
167	1615.3	Bar	222	1662.6	RB	277	1739.6	RB
168	1613.5	Arroyo	223	1661.5	Island	278	1739	Island
169	1612.9	RB	224	1660.8	LB	279	1738.3	RB
170	1608.3	LB	225	1660.7	Island	280	1738.1	Island
171	1608	RB	226	1660.5	LB	281	1737.2	LB
172	1607.3	RB	227	1659.1	Bar	282	1734.4	RB
173	1607.3	Island	228	1657.5	RB	283	1732.6	LB
174	1605.6	Island	229	1657.1	RB	284	1732.3	LB
175	1596.8	Island	230	1655.2	LB	285	1731.5	Arroyo
176	1596.7	RB	231	1654.7	LB	286	1730.8	RB
177	1596.5	RB	232	1650.5	Island	287	1730.4	RB
178	1595.1	Island	233	1649.4	Island	288	1729.6	Island
179	1591.9	LB	234	1648.4	LB	289	1728.4	Island
180	1591.5	LB	235	1647.8	LB	290	1728.1	LB
181	1701.2	RB	236	1645.9	Island	291	1727.5	LB
182	1700.5	RB	237	1645.8	LB	292	1726.7	Island
183	1697.2	RB	238	1645.2	Trib	293	1725.3	Trib
184	1697.1	RB	239	1644.6	RB	294	1724.6	RB
185	1696.6	LB	240	1644.2	RB	295	1724.1	RB
186	1696.2	LB	241	1643.8	Island	296	1723.1	LB
187	1695.9	Island	242	1642.1	LB	297	1722.3	LB
188	1695.1	Island	243	1639.1	RB	298	1720.8	RB
189	1693.6	RB	244	1638.5	RB	299	1719.9	RB
190	1693.2	RB	245	1632.9	RB	300	1717.1	LB
191	1692.9	Island	246	1632.6	RB	301	1716.6	LB
192	1691.9	RB	247	1766.5	LB	302	1714.3	RB
193	1691.5	RB	248	n/a	n/a	303	1712.6	Island
194	1689.4	LB	249	1764.6	LB	304	1712.2	Island
195	1689.1	LB	250	1763.3	LB	305	1711.1	RB
196	1688.4	RB	251	1762.1	Bar	306	1710.4	RB
197	1685.5	Island	252	1761.6	Trib	307	1707.6	LB
198	1682.6	LB	253	1761.3	Island	308	1707.2	Island
199	1681.3	Trib	254	1761.3	RB	309	1706	Island
200	1680.9	Island	255	1760.1	Arroyo	310	1704.9	LB
201	1680.6	Island	256	1759.7	RB	311	1704	RB
202	1680.3	RB	257	1758.2	LB	312	1703.6	Island

Table 4.3 (continued)

GARRISON DAM to BISMARCK, ND								
WPT	RM	Location	WPT	RM	Location	WPT	RM	Location
76	1355.4	RB	101	1378.15	Island	125	1357.7	RB
77	1354.6	RB	102	1377.5	RB	126	1340.55	LB
78	1352.8	LB	103A	1376.6	Island	127	1339.8	LB
79	1352	LB	103B	1376	Island	128	1339.45	Arroyo
80	1351.8	RB	104	1376.1	Island	129	1336.6	RB
81	1352.5	RB	105	1375.4	LB	130	1335.9	RB
82	1351.4	Bar	106	1374.8	LB	131	1335.4	RB
83	1351	Island	107	1375.7	Trib	132	1334.15	Bar
84	1349.7	Island	108	1372.8	LB	133	1334.3	RB
85	1348	Island	109	1372.4	LB	134	1333.6	RB
86	1347	Trib	110	1370.8	LB	135	1333.2	Arroyo
87	1346.65	LB	111	1370.5	LB	136	1331.7	LB
88	1346	LB	112	1369.9	Bar	137	1331.35	LB
89	1342.4	LB	113	1369.6	RB	138	1331	Island
90	1388.5	LB	114	1369	Bar	139	1330	Island
91	1387.1	LB	115	1368.7	Trib	140	1325.5	LB
92	1386.45	RB	116	1367.9	RB	141	1325.15	LB
93	1385.65	LB	117	1365.7	LB	142	1324.7	LB
94	1384	LB	118	1365.3	LB	143	1319.5	Bar
95	1383.7	LB	119	1364.2	RB	144	1317.7	Island
96	1381.7	LB	120	1364.4	RB	145	1317.2	Island
97	1380.3	Island	121	1361.55	Bar	146	1317	Island
98	1380.3	LB	122	1360.9	Bar	147	1316.7	Island
99	1380.4	RB	123	1359.8	LB			
100	1378.45	RB	124	1358.3	RB			
FORT RANDALL DAM to NIOBRARA								
WPT	RM	Location	WPT	RM	Location	WPT	RM	Location
47	841	Island	57	852.6	Island	67	862.2	LB
48	842.4	Bar	58	853.2	Bar	68	863.2	LB
49	844	Trib	59	853	RB	69	864.8	Bar
50	846.8	Bar	60	855.8	Island	70	866.7	Island
51	846.5	Island	61	856.5	RB	71	870.3	LB
52	849.2	RB	62	857.1	Island	72	870.8	LB
53	850	LB	63	858.2	Island	73	875.8	Island
54	850.4	LB	64	858.9	LB	74	875.9	Bar
55	851.1	Island	65	859.4	LB	75	876.6	LB
56	851.4	Bar	66	861.8	LB			
GAVIN'S POINT DAM to PONCA								
WPT	RM	Location	WPT	RM	Location	WPT	RM	Location
1	809	RB	17	796.8	RB	33	777.5	RB
2	806.65	LB	18	796	RB	34	777	LB
3	806.6	LB	19	794.2	LB	35	776.5	LB
4	804.7	RB	20	793.4	LB	36	768.4	LB
5	804.3	RB	21	792.4	LB	37	768	LB
6	804.3	Island	22	783.9	RB	38	765.4	Island
7	803.4	Bar	23	783.5	RB	39	765	LB
8	801.7	RB	24	782.9	RB	40	764.7	LB
9	801	RB	25	781.7	Bar	41	763.3	Island
10	800.8	RB	26	781.1	LB	42	762.8	LB
11	800	Island	27	780.7	LB	43	762.2	LB
12	800.3	Island	28	780.5	Island	44	761.4	LB
13	800.4	Trib	29	780.4	RB	45	756.9	RB
14	800.3	Bar	30	779.5	RB	46	756.6	RB
15	799	Island	31	778.8	Island			
16	796.7	Bar	32	778.4	RB			

4.1.3. Methodology.

4.1.3.1. Banks.

The banks were sampled at fairly regular intervals throughout each of the four main reaches, but concentrating on where they, or any adjacent channel fills greater than about 152 meters (500 feet) in length, were eroding in locations upstream of a bar and island complex. Stable banks were not sampled because they are not contributing to the sediment budget. Sampling sites were visually and/or graphically quartered at 25 and 75% of the erosion reach length, and sampled at these points. Exceptions to this method occurred when the marked reach was significantly interspersed with inactive erosion, or contained lengths of bank with well-established vegetation on the toe. These reaches were subsequently quartered if the left over length was greater than 152 m. If the length was shorter, only one sample was taken. Occasionally very clean erosional faces were present, and if they appeared representative of the reach, the sample was taken at that location. The actual sample was taken from a cleaned face with every facie over 0.3 m (12 inches) thick represented. Where strata were less than 0.3 m (12 inches) thick a composite sample was taken. Figure 4.1 depicts the sampling procedure on the eroding right bank at WPT 149 near RM 1626.8.

4.1.3.2. Bars and Islands.

The bar and island complexes sampled were identified as being downstream of an area of revetted bank, downstream of a major area of eroding bed or bank, or downstream of a tributary input. These sites were marked as complexes to be sampled with two sets of criteria distinguishing sampling sites: heights of land surface above water surface elevation (WSEL), and type of vegetation. The height above WSEL fell into three categories: less than 0.3 m, between 0.3 and 1 m, and greater than 1 m. Figure 4.2 shows a sample location on a Plover habitat bar (Fort Randall Reach, near RM 864.8) where the elevation is 0.3 m or less above this river stage. Similarly vegetation fell into three categories as well: sand, grass and/or shrubs, and trees. Figure 4.3 shows a sample being collected on a vegetated island in the Garrison Reach at WPT 103 near RM 1376.6. The sediment was sampled using a hand-held auger (Figure 4.4). One sample was kept for analysis for every 0.2 m of depth. If the soil in a layer was visually of the same material as the sample in the previous layer, it was not kept.

To ensure that the sampling program defined the underlying material of the bars and islands a minimum sampling depth was set at 20 cm. This minimum depth was used only when the sample site was inundated with water within that sample depth. The maximum sample depth on any bar was 102 cm with an average sample depth of 61 cm.

4.1.3.3. Tributaries.

Specific tributaries were marked for sampling on the aerial maps including the Niobrara, the Poncace, Milk Creek (Figure 4.5), and Knife Creek as well as several arroyos. Tributaries' samples were obtained from the bed. These bed samples were taken more than 100 m upstream of the confluence because eddy effects at the confluence of the two rivers might result in

Figure 4.1 Fort Peck Reach – sampling eroding right bank at WPT 149, RM 1626.8.

Figure 4.2 Fort Randall Reach – Plover habitat bar at WPT 069, RM 864.8.

Figure 4.3 Garrison Reach – sampling vegetated island at WPT 103, RM 1376.6.

Figure 4.4 Fort Randall Reach – core sampler on island at WPT 073, RM 875.8.

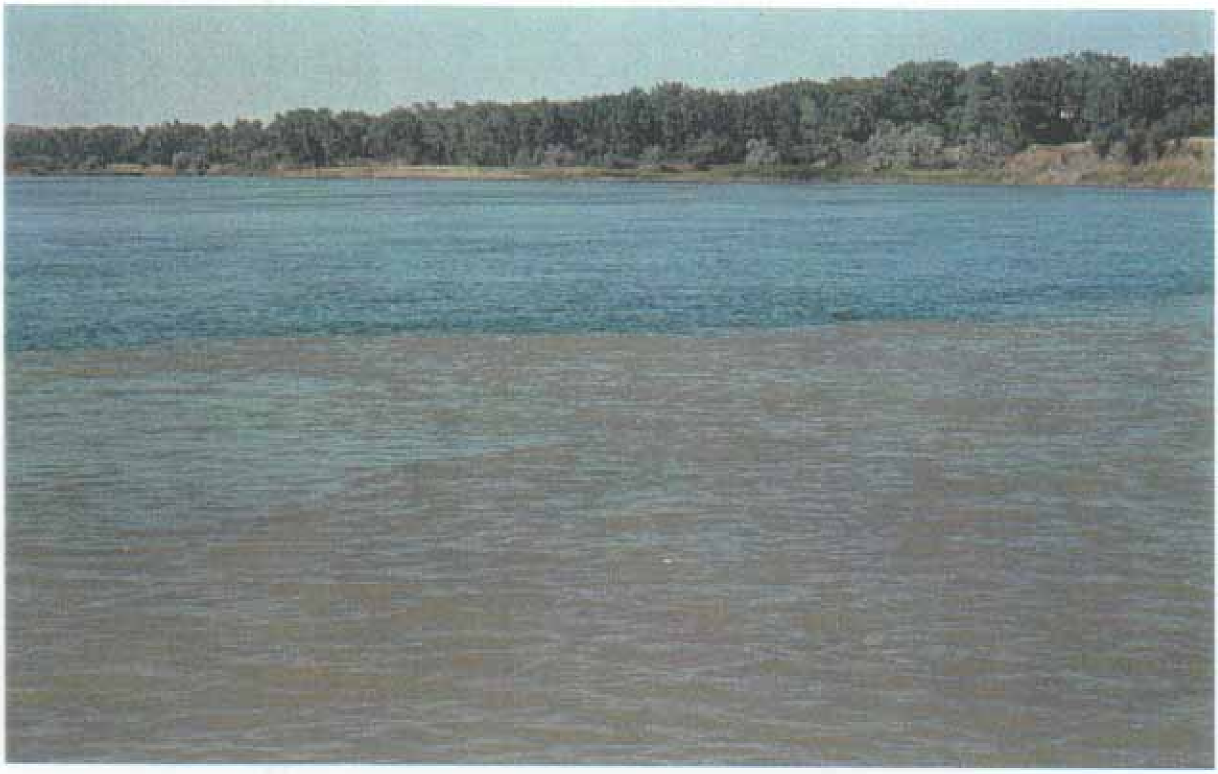


Figure 4.5 Fort Peck Reach – Milk River sample site at WPT 252, RM 1761.6.

sediments from the main channel being deposited inside the mouth of the tributary. A hand-held sediment corer was used to collect the samples over the edge of the boat. Three samples were collected across each channel width. This procedure was used for all but one tributary that was no more than 3-m across. Only one sample was taken in the approximate center of this small tributary.

4.1.3.4. Arroyos.

The ephemeral tributaries sampled (i.e., arroyos) were only those which flow directly into the Missouri. The sediment samples at these sites were taken with a hand-held auger as outlined in the bar and island section. The samples were taken in the approximate center of the arroyo (Figure 4.6). The only obvious arroyo's were encountered in high bluffs. Other arroyo's had to be distinguished from true runoff access points, and cattle paths leading to the water's edge.

Figure 4.6 Fort Peck Reach – arroyo at WPT 285, RM 1731.5.

4.2. Laboratory Analysis of Sediment Samples

In order to establish the sediment budget for the four study reaches of the Upper Missouri River it is necessary to analyze the particle size distributions of sediment samples from the tributaries, the banks, the bed, and the bars and islands of the Missouri River. A total of 655 sediment samples at 312 sites or 'waypoints' were collected by a field team from the Engineering Research Center (ERC) at CSU during the summer of 1999. At each waypoint, one or more samples were collected depending on if there were significant changes in stratigraphy or grain size in the layers at that site. Over the course of the following year these samples were dry sieved to obtain the grain size distributions in the range between 0.063 mm and 42 mm. The data were tabulated as Percent Finer on each sieve size and includes columns for percentile values such as: D_{84}, D_{50}, and D_{16} where the grain size for which D_{xx} of the material is finer is given. The geometric standard deviation is also given in a column titled 'sigma'. Table 4.4 shows a sample of the results, which are included in their entirety in Appendix A of the data supplement that accompanies this report. The file on the data supplement CD ROM contains five worksheets. The first worksheet contains the sieve analysis results as shown in Table 4.4 for all of the samples. Worksheets two through five are catalogs of the waypoints for each reach including: WPT number, approximate river mile, and location.

Table 4.4 Sample table – Missouri River sediment samples for Gavins Point.

Reach	WPT	Sample No.	Layer/ Type	Percent Finer on Sieve Size (mm)															Percentiles					Sigma
				42	32	22.4	16	8	5.6	4.75	4	2	1	0.5	0.25	0.125	0.075	0.063	D_{84}	D_{50}	D_{16}	D_{90}	D_{10}	
Gavins Pt	2	1	1	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	93.4%	80.1%	71.6%	66.1%	61.6%	53.6%	47.2%	1.23	0.07	n/a	1.68	n/a	n/a
Gavins Pt	2	2	2	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	99.8%	99.2%	94.7%	55.6%	24.8%	18.3%	0.21	0.11	n/a	0.23	n/a	n/a
Gavins Pt	2	3	3	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	99.9%	98.4%	87.9%	47.8%	20.8%	13.6%	0.23	0.13	0.07	0.29	n/a	1.87
Gavins Pt	2	4	4	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	99.6%	98.2%	90.9%	53.3%	3.5%	3.3%	0.6%	0.44	0.24	0.15	0.49	0.14	1.72
Gavins Pt	3	5	1	100.0%	100.0%	100.0%	100.0%	99.7%	98.3%	97.2%	95.8%	90.7%	84.6%	79.3%	74.7%	56.9%	39.4%	33.7%	0.93	0.10	n/a	1.86	n/a	n/a
Gavins Pt	3	6	2	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.8%	99.0%	95.3%	31.2%	17.1%	12.1%	0.22	0.15	0.07	0.24	n/a	1.75
Gavins Pt	3	7	3	100.0%	100.0%	100.0%	100.0%	100.0%	99.8%	99.8%	99.6%	99.4%	98.9%	95.9%	84.2%	30.6%	18.0%	13.7%	0.25	0.16	0.07	0.35	n/a	1.90
Gavins Pt	3	8	4	100.0%	100.0%	100.0%	100.0%	99.9%	99.7%	99.5%	99.2%	98.5%	97.0%	94.7%	90.0%	16.8%	10.8%	7.1%	0.24	0.17	0.12	0.25	0.07	1.42
Gavins Pt	4	9	1	100.0%	100.0%	98.7%	93.5%	87.1%	85.0%	84.2%	83.5%	81.6%	79.9%	78.0%	74.6%	56.9%	41.4%	36.1%	4.52	0.10	n/a	10.96	n/a	n/a
Gavins Pt	4	10	2	100.0%	100.0%	100.0%	99.7%	99.4%	99.1%	98.7%	98.3%	96.4%	94.5%	88.0%	28.1%	5.2%	2.4%	1.4%	0.48	0.32	0.17	0.62	0.14	1.66

4.3. Geology

An effort was made to determine from the literature the major geologic formations immediately adjacent to the Upper Missouri River for the four study reaches. Some information was found for the Fort Randall, Gavins Point, and Garrison Reaches and was compiled in two summaries: "Formations Adjacent to the Missouri River, Fort Randall Reach and Gavins Point Reach, Nebraska, and Southeastern South Dakota" and "Geology of the Missouri River, Garrison Reach, Southwest North Dakota." These summaries are included in Appendix B on the data supplement CD ROM that accompanies this report. The information about bedrock types adjacent to the river was included in the geomorphic characterization and classification of the reaches as well.

4.4. Specific Gauge Analysis

Perhaps one of the most useful tools available to the river engineer or geomorphologist for assessing the historical stability of a river system is the specific gauge record. According to Blench (1966):

> *There is no single sufficient test whether a channel is in-regime. However, for rivers, the most powerful single test is to plot curves of "specific gage" against time; if the curves neither rise nor fall consistently the channel is in-regime in the vicinity of the gaging site for most practical purposes.*

A specific gauge record is simply a graph of stage for a specific discharge at a particular gauging location plotted against time. A channel is considered to be in equilibrium if the specific gauge record shows no consistent increasing or decreasing trends over time, while an increasing or decreasing trend is indicative of an aggradational or degradational condition, respectively.

The specific gauge analysis of the Missouri River performed in this study is based on data obtained from two sources. The most complete source of at-a-station data are the USGS 9-207 forms that contain details of the measured stages and discharges for each USGS station for the period of operation of that station. These data are collected approximately six to eight times a year and, because they list the actual measurements of both stage and discharge obtained in the field, they are the most complete available measurements. The second source is USAEDNMRR (1994), which contains specific gauge plots for all of the stations in the four reaches being studied and thus provides more comprehensive spatial coverage at reach scale than that of the 9-207 stations. The data taken from these plots, however, are slightly less complete because not all the stations record both measured stages and discharges. The missing data must be obtained from the rating curves constructed for each station. Furthermore, the rating curves may be extrapolated beyond the range of measured data in both directions, depending on whether the year in question was particularly wet or dry.

For gauging stations where data were available from both sources, data were combined onto a single graph. This produces a longer period of record because the 9-207 data generally only extends back to the mid- to late-1970s, while the data from USAEDNMRR (1994) frequently extends back to the 1960s or the 1950s – very near to the time when the dams in the Garrison, Fort Randall and Gavins Point Reaches were constructed.

Tables 4.5 through 4.8 show the gauge locations, period of record, and flows included in the specific gauge analysis for all four study reaches. The locations of these gauges are also shown on the vicinity maps for each reach in Chapter 5. The actual specific gauge records are shown in Appendix C on the data supplement CD ROM.

Table 4.5 Fort Peck Reach specific gauge data.

Station Name	1960 RM	Discharge (CMS)	Years of Records
Gauge No. 1	1768.9	283	1950-1975
		566	1950-1975
		850	1950-1975
7 Mile Gauge	1763.5	283	1950-1984
		566	1950-1984
		850	1950-1966
Milk River at Nashua	1761.6	6	1978-1998
		42	1984-1998
		99	1984-1998
West Frazer Pump Plant	1751.3	283	1950-1984
		566	1950-1984
		850	1950-1984
East Frazer Pump Plant	1736.6	283	1950-1984
		566	1950-1984
		850	1950-1984
Oswego	1727.6	283	1950-1966
		566	1950-1966
		850	1950-1966
Missouri River near Wolf Point	1701.22	212	1977-1999
		283	1950-1999
		396	1975-1999
		566	1950-1984
		850	1950-1984
Poplar River near Poplar	1678.9	2	1984-1999
		11	1984-1999
Missouri River near Culbertson	1620.76	212	1985-1998
		283	1950-1998
		566	1950-1984
		850	1950-1984
Yellowstone River near Yellowstone	1582	255	1976-1999
		637	1974-1999
		906	1974-1999

Table 4.6 Garrison Reach specific gauge data.

Station Name	1960 RM	Discharge (CMS)	Years of Records
Missouri River near Stanton	1378.4	283 566 850	1950-1997 1950-1977 1950-1977
Knife River near Hazen	1375.5	1 21	1987-1999 1990-1999
Missouri River near Fort Clark	1366.65	283 566 850	1960-1997 1960-1997 1960-1997
Missouri River near Hensler	1362	283 566 850	1959-1997 1959-1997 1959-1997
Missouri River near Washburn	1354.7	283 566 850	1955-1997 1955-1997 1955-1997
Missouri River near Price	1338	283 566 850	1960-1986 1960-1986 1960-1986
Missouri River at Bismarck	1314.2	467 688	1987-1999 1989-1999

Table 4.7 Fort Randall Reach specific gauge data.

Station Name	1960 RM	Discharge (CMS)	Years of Records
Fort Randall Dam Gauge	879.98	283 566 850	1953-1986 1953-1986 1953-1986
Missouri River below Greenwood	865.04	283 566 850 1133	1966-1987 1967-1987 1966-1987 1967-1987
Missouri River Gauge at RM 853.37	853.37	566 850 1133	1960-1972 1960-1972 1960-1972
Ponca Creek near Verdel	848.9	1 8 37	1957-1998 1957-1998 1960-1998
Missouri River near Verdel	845.91	566 850 1133	1964-1985 1964-1985 1964-1985
Niobrara River near Verdel	844	40 65 93	1958-1997 1958-1997 1958-1997
Missouri River near Niobrara	842.45	566 850 1133	1956-1985 1956-1985 1956-1985

Table 4.8 Gavins Point Reach specific gauge data.

Station Name	1960 RM	Discharge (CMS)	Years of Records
Missori River at Yankton	805.8	566 779	1973-1995 1973-1995
James River near Yankton	800	8	1982-1993
Missouri River near Gayville	796	283 566 850	1955-1997 1955-1997 1955-1997
Missouri River near Maskell	775.8	283 566 850 1133	1955-1995 1955-1997 1955-1997 1955-1997
Vermillion River near Vermillion	772	6 23 48	1983-1999 1983-1999 1983-1999

4.5. HEC-RAS Analysis

Hydrologic Engineering Center's River Analysis System (HEC-RAS) is a computer program which performs one-dimensional steady flow calculations (USACE 1998). Its backwater calculation method for determining water surface profiles was used to determine channel hydraulic characteristics including: thalweg elevation, thalweg depth, top width, friction slope, bed slope, flow area, wetted perimeter, and hydraulic radius at each cross section for each of the four study reaches. Input data included the cross-section station and elevation data, downstream water surface and slope information, and discharge. Cross-sectional data were obtained in HEC-DSS format and converted for input into the HEC-RAS program. Information was available for two or three years for each reach.

Minimum, maximum, and average discharges were calculated from data tables given in a previous USACE report (Pokrefke *et al.* 1998) and applied to each year's set of cross-section data for the Fort Peck, Garrison, Fort Randall, and Gavins Point Reaches. The discharge values are based on monthly averages over the time period 1898-1993. Table 4.9 is an example of the results tables generated from the HEC-RAS analysis. It presents data based on 7 cross sections for the Fort Randall Reach during 1979 at a maximum discharge of 950 CMS. The complete set of tables is presented in Appendix D on the accompanying data supplement CD ROM.

Table 4.9 Sample table – HEC-RAS analysis hydraulic data results for the Fort Randall Reach 1979, discharge = 950 CMS.

River Station	RM (mi)	Thalweg Elevation (ft)	WSEL (ft)	Thalweg Depth (ft)	Top Width (ft)	Friction Slope (ft/ft)	Bed Slope (ft/ft)	Flow Area (sq ft)	Wetted Perimeter (ft)	Hydraulic Radius (ft)
7	895.6	1197	1223.81	26.81	3626.07	0.000087	-0.000485	23461.53	3640.31	6.44
6	893.1	1203.4	1222.62	19.22	1223.48	0.0001	0.000054	15898.86	1227.99	12.95
5	891.7	1203	1221.89	18.89	2911.5	0.000089	0.000758	19656.13	2923.04	6.72
4	890.2	1197	1221.2	24.2	5234.66	0.00012	0.000073	30236.56	5246.8	5.76
3	888.9	1196.5	1220.33	23.83	3923.34	0.000291	-0.000081	17409.02	3933.83	4.43
2	886.8	1197.4	1217.06	19.66	2035.61	0.000336	0.000379	13182.44	2044.1	6.45
1	885.6	1195	1214.93	19.93	2418.36			13142.5	2427.8	5.41

4.6. Grain Size Analysis

4.6.1. Introduction.

This section details the steps in developing a quantitative analysis of the grain size distributions of sediment samples from the tributaries, the banks, and the bars and islands of the Missouri River.

4.6.2. Methodology.

The first stage of the analysis involved plotting percentile curves for each sample that was collected. Where more than one sample existed for a sampling location (referred to as waypoints), (for example from several different sedimentary strata within a bank), all the points were plotted onto the same chart so that differences between the layers could be observed. Figure 4.7 is an example plot from the Fort Peck Reach which shows the grain size distributions for three layers of stratigraphy at one sampling location, WPT 266, which is near RM 1750.2 on the left bank. The complete set of charts is shown in Appendix E on the data supplement CD ROM.

The next stage involved combining the individual sample data for all the waypoints where more than one sample was collected. To ensure that the relative proportion of material contributed from each sample in a multiple layer bank waypoint was accurately represented in the composite sample, it was necessary to multiply each individual size fraction in the sample by the fraction of the bank height occupied by that layer. This approach makes the assumption that the bank fails over its full height and that all of the material is available for transport in the system. When creating a composite particle size distribution from a number of individual samples from a tributary or arroyo bed for which no layer thickness' are given, an arbitrary thickness value of 0.304 m was allocated to each sample to ensure that they received equal weighting in the compositing process. Island or bar samples for which no percentage coverage or areal extents of the particular facies being sampled are recorded were also treated in the same fashion. This makes it possible for one weighted percentile curve to be plotted for each waypoint and thus serve as the basis for the comparisons between bank and bar/island sediments.

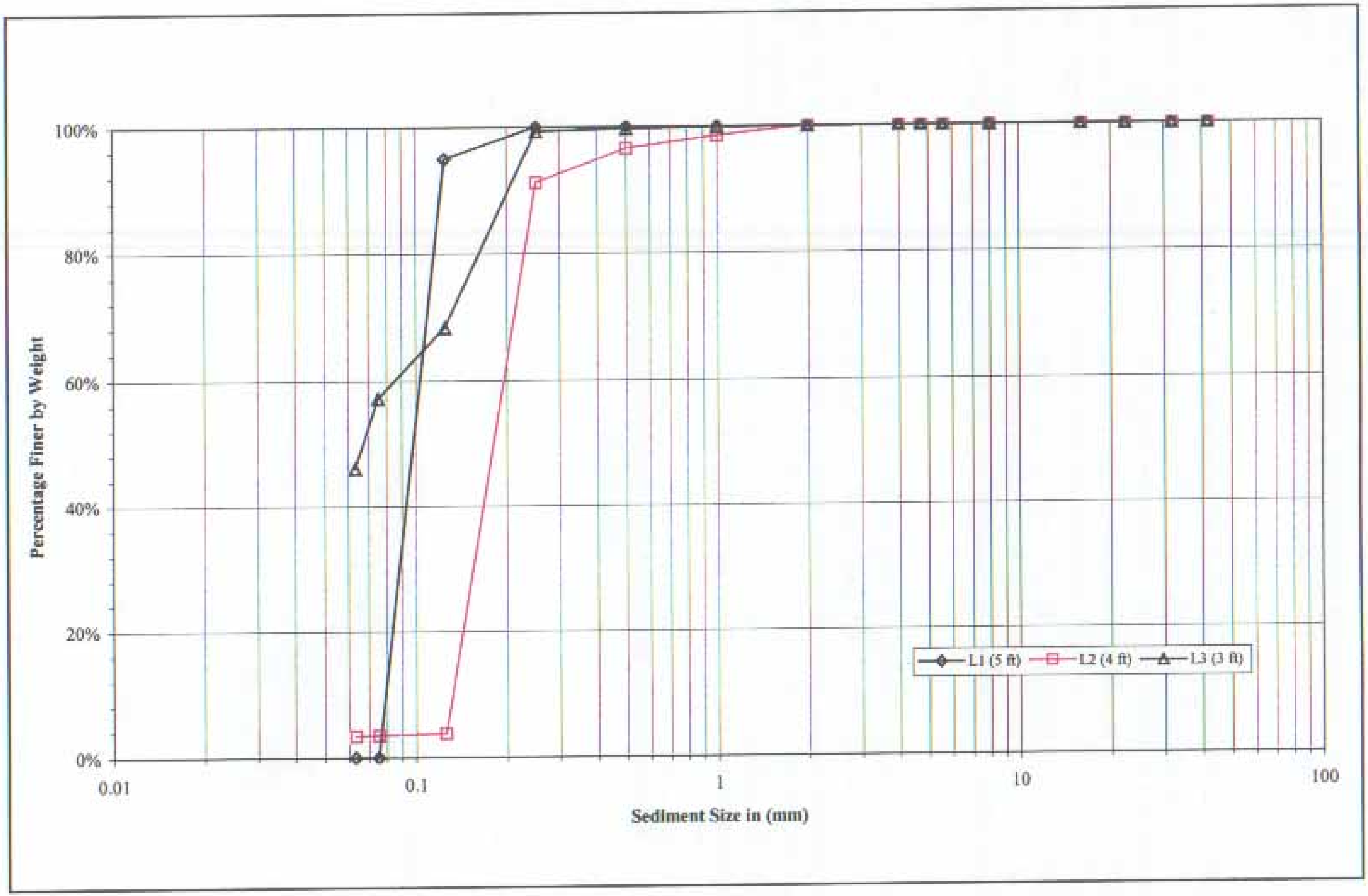


Figure 4.7 Example plot – Fort Peck Reach, left bank, RM 1750.2 (WPT 266).

4.7. Measured Suspended Data

Measured suspended sediment data were acquired from an USGS station at Culbertson, Montana, in the Fort Peck Reach and at Bismarck, North Dakota, in the Garrison Reach. No main stem Missouri River suspended sediment data were available in the Fort Randall and Gavins Point Reaches.

Measured suspended sediment data were available at Culbertson, Montana, for the period 1971 to 1999. A sediment rating curve was developed from the observed data with suspended sediment discharge as a function of water discharge (Figure 4.8). Also shown in Figure 4.8 is the polynomial regression for the data. This polynomial relationship was then applied to the daily discharge record from 1971 to 1999 to produce the total measured suspended sediment load for each year. Based on this analysis, the average annual measured suspended sediment load at Culbertson is about 1,700,000 m^3/yr. Gradation data indicate that the average sand fraction of this load is about 40%. Therefore, the average annual measured sand load is about 680,000 m^3/yr.

At Bismarck, North Dakota, measured suspended sediment data were available from 1972 to 1989. The rating curve and regression for this data are shown in Figure 4.9. This regression was applied to the daily discharge data for the period 1972 to 1999 to produce the total measured suspended load for each year. Based on this analysis, the average annual measured suspended sediment load at Bismarck is about 2,115,000 m^3/yr. No gradation data were available to determine the sand fraction of this load.

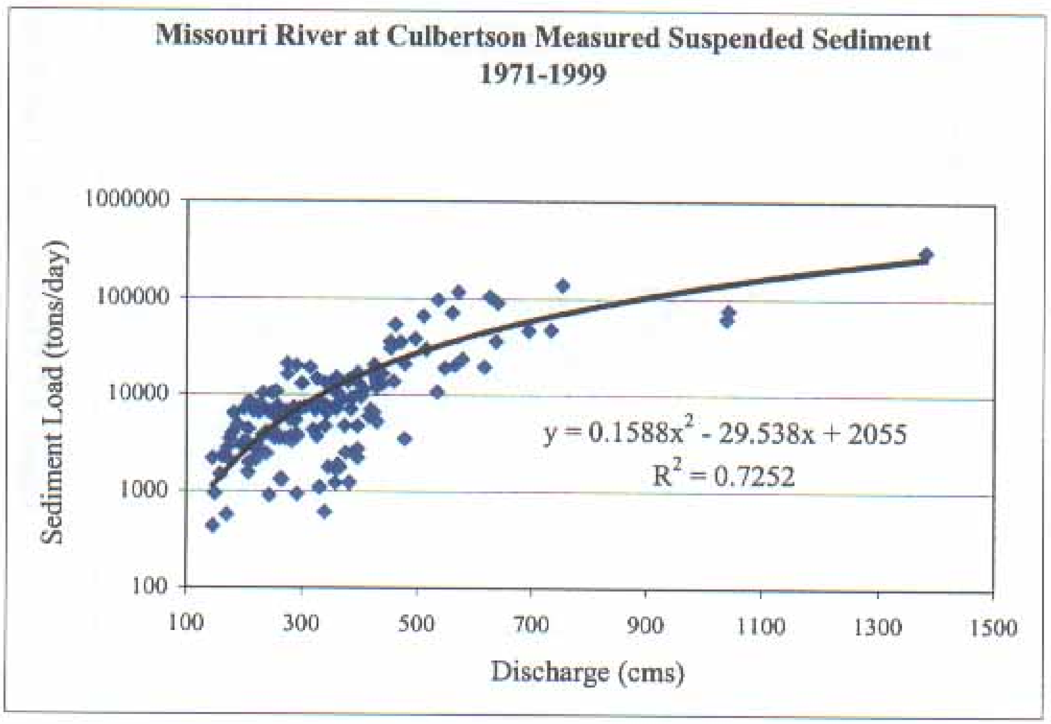


Figure 4.8 Sediment rating curve for Culbertson, Montana.

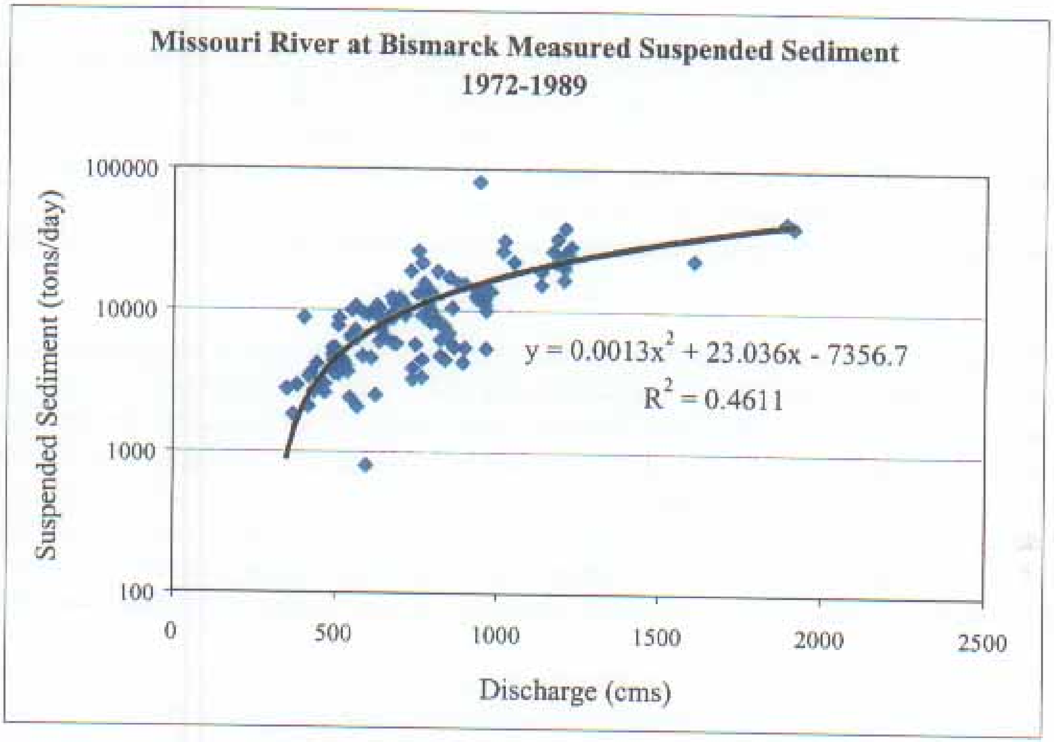


Figure 4.9 Sediment rating curve for Bismarck, North Dakota.

4.8. Sediment Transport Calculations

4.8.1. Introduction.

The sediment transport capacity, or sediment yield, of the Gavins Point and Fort Peck Reaches were calculated using the computer program SAM a Hydraulic Design Package for Channels (Copeland 1999). The SAM calculations are based on the bed grain size distribution, channel geometry, and flow duration curves. The SAM calculated values were then compared to the sediment budget values described in detail in Section 4.13. The accuracy of each approach is uncertain to the degree that input values are estimated and data are available.

4.8.2. General Procedure.

In order to use SAM to calculate the sediment yield on the Gavins Point and Fort Peck Reaches of the Missouri River, input data were compiled from a variety of sources. The steps and data sources involved are listed in sequence below as are the assumptions and decisions used to proceed.

The Gavins Point and Fort Peck Reaches were subdivided into geomorphic reaches (GRs) that are described in the Geomorphic Reach Classification, Section 4.9, of this report. Within each of these reaches a cross section was chosen from the Sediment Ranges of historical survey data reported in "Missouri River Gavins Point Dam Degradation Trends Study" (USACE 1996) and "Fort Peck Project, Montana: Downstream Channel and Sediment Trends Study" (Midwest International 1997). The 1978 sediment range data were used for the Fort Peck Reach to establish the cross sections as was the 1978 active channel discharge and water surface elevations. The 1978 data set was more complete in the HEC-RAS analysis through coverage of all of the GRs. The 1986 data were used for the Gavins Point Reach. The actual station and elevation data for each cross section had been compiled earlier for a HEC-RAS analysis and was downloaded from those files.

The grain size distribution for the Gavins Point Reach was a composite of all of the habitat bar distributions on the reach because only GR 1 and GR 2 had habitat bars. The grain size at which 10% of the material was finer (0.2 mm) was used as the cutoff for the distribution. This is due to the sensitivity of transport calculations to the grain size, especially the finer sizes, and Einstein's (Einstein 1950) recommendation to exclude the finest 10 percent of the sampled bed gradation from calculations of the total bed-material load. The goal here was to focus on the transport of the material found in the habitat bars to determine what proportion of the material capable of transport was available from the banks and could contribute to habitat bar formation.

The Fort Peck Reach had more diversity of grain size distributions in the habitat bars than the Gavins Point Reach so the individual GRs used the distributions from within that reach or adjacent reaches. For instance, GR 1 had no habitat bars sampled so the distribution for the habitat bar in GR 2 was used. The habitat bar distribution for GR 4 is extremely fine, and not considered representative of habitat bars throughout the reach so a grain size distribution from GR 5 was used in this case. Table 4.10 lists in the header row the Habitat Bar (HB) waypoint numbers of the grain size distributions used. The grain size 0.16 mm was used as the cutoff for the distribution. This value was chosen to match the cutoff used for the sediment budget portion of the study described in Section 4.13 so that the values for sediment yield could be compared.

The flow duration curves required to calculate the sediment yield in cubic yards per year was taken from the WES Report (Pokrefke *et al.* 1998) data on average daily flows for the period 1981 – 1993. This interval is most inclusive of the dates used to calculate bank line erosion rates from the aerial photographs.

SAM was run for 7 transport equations including: Toffaleti, Ackers-White, Colby, Toffaleti-Schoklitsch, Engelund (Hansen), Van Rijn, and Laursen (Copeland). The Toffaleti equation was found by the study "Verification of Sediment Transport Functions" (USACE 1980) to best fit observed data for predicting bed material load and particle size distribution downstream of the Gavins Point Reach and was used only for the Gavins Point SAM calculations. Ackers-White was found by the same study to give the best predictive accuracy when dealing with bed material only. A utility within the SAM program called SAM.aid suggested the other five functions as being the best fits for the river based on the velocity, depth, slope, width, and D_{50}.

4.8.3. Results.

The results from the yield analysis using SAM returned values for total yield that were similar to those calculated using data based on sediment ranges and measured bank erosion rates (Tables 4.10 and 4.11) when comparing the best fit data. The range of percent differences from 1 to -28% for the Gavins Point Reach is within the range of uncertainty of using the different transport equations in SAM. Even the difference between Toffaleti and Ackers-White (about 60%) which were studied and found to be best fits for the river just downstream of the Gavins Point Reach (USACE 1980) is greater than the difference between the two methods of calculating the yield. The Fort Peck Reach also showed reasonable agreement between the two methods of calculating the total sediment yield for each GR except in GR 1 where the percent difference is about 170% higher for the SAM analysis than the measured erosion and deposition rates. What this reflects is that there may be a higher capacity for the channel to transport sediment in this reach then it is transporting. However, there are too many variables and not enough data to tell why this difference is so great.

Table 4.10 Fort Peck Reach SAM sediment calculations by geomorphic reaches.

Transport Function	Sediment Yield in 1,000's m^3 /yr							
	GR 1 HB 303	GR 2 HB 303	GR 3 HB 303	GR 4 HB 211	GR 5 HB 211	GR 6 HB 227	GR 7 HB 167	GR 8 HB 178
Ackers-White	452	166	1028	582	1506	399	738	773
Engelund Hansen	548	386	2048	620	2743	626	801	846
Colby	838	160	1289	152	1653	565	1652	1733
Van Rijn	276	58	606	655	1463	199	722	817
Laursen (Copeland)	553	163	761	1263	1016	409	990	1272
Toffaleti-Schoklitsch	251	120	752	573	1245	280	611	940
Budget Analysis Results	91	315	389	644	842	857	732	732
Closest match	TS (251)	EH (386)	VR (606)	VR (655)	LC (1016)	EH (626)	AW (738)	AW (773)
% difference	176	22	56	2	21	-27	1	6

Table 4.11 Gavins Point Reach SAM sediment calculations by geomorphic reaches.

Transport Function	Sediment Yield in 1,000's m^3/yr			
	GR 1	GR 2	GR 3	GR 4
Toffaleti	358	837	220	740
Toffaleti-Schoklitsch	489	1,303	417	975
Ackers-White	829	2,113	316	1,813
Colby	1,311	2,972	177	3,143
Engelund Hansen	1,334	3,665	1,496	2,511
Budget Analysis Results	463	1198	2082	2813
Closest match	TS (489)	TS (1303)	EH (1496)	EH (2511)
% difference	6	9	-28	-11

4.9. Geomorphic Reach Classification

4.9.1. River Channel Classification.

River channel classification is a means of reducing a complex system into a series of more easily understandable units, which in turn facilitates further study and the organization of management options. A distinction needs to be made between schemes that *classify* rivers and schemes that *characterize* them. The former involves a subdivision of the river channel into discrete reaches according to designated criteria, whereas the latter concurrently uses multiple criteria that allow the formation of statistically distinct groupings. There are a wide variety of types of classification schemes. Morphological classifications proceed on the basis of the existing channel features, whereas other schemes classify on the basis of river channel adjustment by distinguishing active processes from the facets of the existing morphology. A third type of classification provides information about the conservation value of the river by noting the differences between the existing channel morphology and the morphology that would exist without the effects of human disturbances (Downs 1995).

Both a classification and a characterization scheme are applied in this study. First, the four study reaches are characterized by identifying Geomorphologic Reaches (GRs) and, second, the river is classified according to the system developed by Brice (1975).

4.9.2. Geomorphic Reaches.

Identification of GRs involves breaking down each main reach into discrete sub-reaches based on similarities in form and process. Both quantitative and qualitative techniques were employed to synthesize data from a variety of sources. First, summary tables of data were compiled for the four reaches. These include information on whether the banks are eroding or accreting and the location of this activity (i.e., inside of the bend, outside of the bend or at a crossing); the results of Pokrefke *et al.*'s (1998) analysis into rates of erosion and deposition along both banks and the bed, reach-scale trends of bed aggradation and degradation based on the findings of various workers (USACE 1986, 1994; Dangberg *et al.* 1988a, b; Midwest International, Inc. 1997; WEST Consultants, Inc. 1998); and on the solid and drift geology in which the river is located. Second, the cross-sectional data for each reach was input to HEC-RAS and, by running the maximum mean monthly discharge, the bed slope, energy slope, velocity, width-depth ratio, hydraulic radius, and conveyance were calculated. These parameters, along with sinuosity the locations of left and right bank revetments, and the bar and island densities from Pokrefke *et al.* (1998) were compiled. Finally, aerial photograph mosaics from the mid-1980s and late-1990s were examined to see the variations in degrees of meandering and braiding.

Taken together, these three compilations of data were used to identify reaches that had consistent planform and hydraulic properties and where similar processes appeared to be occurring. For instance, when a clear change from a meandering to a straighter and more braided planform was noticed on the photographs, the plots of the hydraulic variables would be examined to see if any of the trend lines showed a significant change in pattern at a similar river mile location. This was frequently the case and so this location was chosen as a boundary to a GR. It is important to note that changes in planform do not necessarily occur at exactly the same location as changes in the hydraulic variables or as changes in geology, but generally within a few river miles. This is because rivers are natural systems that exhibit a continuum of channel form, which is a function of the driving variables and boundary conditions of the particular physiographic region in which the river is located (Thorne 1997). As a result, it is only natural to expect a certain degree of spatial lag between the point when a particular driving variable begins to change and the point when a threshold is crossed that allows a change in form to occur. The selection of the precise location of the boundary to the GR is thus subjective to a certain degree, in that it represents the personal opinion of the workers involved as to what are the most significant factors for the project out of all the data being considered. The limits and brief discussion of each GR for the four study reaches is given in Tables 4.12 through 4.15.

Table 4.12 Geomorphic reaches for Fort Peck Reach.

GR (1960 RM)	Criteria
GR 1 (1766-1750)	A zone of adjustment downstream from the dam (intense degradation to RM 1757.3) along with extensive right bank bluff line control (RM 1764-RM 1763.4; RM 1760.3-RM 1759.8; and RM 1757.7- RM 1756.2); decreasing energy and bed slopes; increasing conveyance and hydraulic radius.
GR 2 (1750-1713)	Greater planform sinuosity and larger meander arc lengths; less bluff line control and evidence of greater meander migration across the floodplain – extensive scroll features are visible; bed slope decreases to about RM 1725; RM 1725-RM 1715 appears to be transition zone between the meandering planform upstream of this 10-mile reach and the more braided planform downstream.
GR 3 (1713-1700)	The meander migration is less intense than in the previous reach due to the less extensive scrolling visible on the 1998 aerial mosaics and there is a greater degree of braiding than in the previous reach; right bank bluff line contact occurs from RM 1711.4-RM 1711.1 and RM 1701.6-RM 1701.2; energy slope and conveyance both increase to RM 1700.
GR 4 (1700-1686)	There is even less planform migration than in the previous reach (fewer scroll features on the floodplain in the 1998 aerial mosaic). Sinuosity is lower and the degree of braiding more intense than in the previous reach; right bank bluff line control occurs from RM 1695.9-RM 1694.7; RM 1692-RM 1691.8 and RM 1688.6-RM 1688.2; bed slope increases and w:d ratio decreases to RM 1688.
GR 5 (1686-1654)	A highly sinuous planform (2.13) due to active meandering across the floodplain, as evidenced by meander scroll topography and the relative absence of bluff line control. The hydraulic variables show trends that continue through this reach and into reach 6 downstream. (From RM 1686-RM 1625 bed slope, energy slope, velocity and w:d ratio all decrease, whilst conveyance and hydraulic radius both increase).
GR 6 (1654-1621.7)	The hydraulic variables continue the trends started in the previous reach but the meandering changes from active to passive due to probable geologic controls. Right bank bluff line contact occurs from RM 1653.7-RM 1652.1; RM 1639.8-RM 1639.3; RM 1635.85-RM 1635.5; RM 1633.2-RM 1633.05; RM 1627.3-RM 1626.7; and RM 1622.7-RM 1622.5. The sinuosity of this reach is 1.39.
GR 7 (1621.7-1605)	Sinuosity again shows a decrease, to a value of 1.08 and the reach is still exhibiting the characteristics of passive meandering. Bluff line control occurs along the right bank from RM 1617.9-RM 1617.8 and RM 1612-RM 1610.55, and along the left bank from RM 1614.3-RM 1613.8 and RM 1609-RM 1608.15. No hydraulic variable data are available downstream of RM 1620 since no cross sections exist beyond this point.
GR 8 (1605-1582)	Sinuosity increases to 1.37. From RM 1605-RM 1590 the floodplain is less constricted by bluffs and the channel is allowed to meander freely, to the extent that a very large cutoff has occurred at RM 1599.5. Bluffs constrict the valley for a few miles downstream of RM 1590 before again opening out around the confluence with the Yellowstone River.

Table 4.13 Geomorphic reaches for Garrison Reach.

GR (1960 RM)	Criteria
GR 1 (1390-1376)	The energy slope and w:d ratio show a rapid rate of increase to the downstream limit of this reach, whilst the conveyance and hydraulic radius both show a very rapid rate of decrease to the same point. The downstream limit to this reach is 0.5 miles upstream of the Knife River tributary.
GR 2 (1376-1363)	The planform initiates an abrupt and significant change in direction at RM 1373 and this may be due to the input of the Knife River 3 miles upstream; bed slope and hydraulic radius begin to decrease at RM 1373, whilst the w:d ratio shows a decreased rate of increase at this point; the energy slope decreases gradually from RM 1376 before decreasing rapidly at RM 1373.
GR 3 (1363-1353)	An abrupt change in planform occurs at RM 1363; between RM 1364.1 and RM 1362.7 the bed begins to aggrade; energy slope levels out at RM 1363 before beginning to drop off sharply at RM 1356; hydraulic radius drops sharply at RM 1363; a small amount of left bank bluff line contact occurs from RM 1361.3-RM 1361.1.
GR 4 (1353-1340)	Significant bluff line control of meandering – on the right bank from RM 1347.9 to approximately 1346.9 and on the left bank from RM 1342.7-RM 1342.6 and RM 1342.2-RM 1341.6; extensive left and right bank protection from RM 1351.5-RM 1348.1; w:d ratio decreases sharply and hydraulic radius increases sharply at RM 1353; the reach is heavily braided.
GR 5 (1340-1324.5)	The bluff control is absent and the reach is again very heavily braided; bedrock changes from Bullion Creek Formation to shale, siltstone and sandstone at RM 1340; the hydraulic variable plots only extend to RM 1336, but there appears to be an abrupt change to several of the trends at RM 1337 – w:d ratio shows a sharp increase whilst both hydraulic radius and conveyance decrease sharply.
GR 6 (1324.5-1311)	There are extensive sections of bank protection along both banks: on the left bank from RM 1324.6-RM 1320.3 and RM 1315.7-RM 1311 and on the right bank from RM 1321.9-RM 1320.15; RM 1318.2-RM 1315.9; and RM 1313.9-RM 1313.1; the reach is still heavily braided although probably less so than reaches GR 4 and GR 5, but there are two large and heavily dissected bar and islands complexes from RM 1324.2-RM 1322 and RM 1318.2-RM 1316.

Table 4.14 Geomorphic reaches for Fort Randall Reach.

GR (1960 RM)	Criteria
GR 1 (880-873.9)	The channel experiences left bank bluff line control from RM 878.5-RM 876 and there is a large bar/island complex from RM 876-RM 874.4; energy and bed slope, velocity and hydraulic radius all decrease to RM 875, whilst w:d ratio and conveyance both increase to this point.
GR 2 (873.9-867.5)	There is right bank bluff line control of the channel from RM 874-RM 869.8; energy slope and velocity increase sharply from RM 872-RM 868 whilst w:d ratio shows a gradual decrease over this distance; conveyance decreases considerably from RM 872-RM 867.
GR 3 (867.5-861.7)	The energy slope and velocity plots show a large decrease from RM 868-RM 862.5 whilst conveyance shows a large increase over the same distance.
GR 4 (861.7-854.5)	There is right bank bluff line control over the full extent of the reach, which is also a zone of transition between the dam–related degradation and the downstream zone of aggradation; energy slope, velocity and w:d ratio all increase throughout most of this reach, whilst hydraulic radius and conveyance both decrease.
GR 5 (854.5-851)	There is no bluff line control in this reach; energy slope decreases sharply to RM 851 whilst velocity also decreases; w:d ratio increases gently; conveyance and hydraulic radius increase sharply from approximately RM 853.25-RM 851 and RM 852.25-RM 851, respectively; the upstream limit of this reach begins the zone of bed aggradation that is probably due to the backwater effect created by Lewis and Clark Lake and the delta that has been deposited at the confluence with the Niobrara River at RM 844; braiding is much more extensive than in the previous reaches.
GR 6 (851-844)	There is left bank bluff line control from RM 851.2-RM 850.5. The present morphology of the channel is controlled by the backwater effects and the extensive deposition that has occurred as a result, and braiding and chuting are extensive throughout; energy slope decreases fractionally from RM 851-RM 849 before increasing very sharply to RM 844; similarly, conveyance increases slightly before decreasing rapidly; over the same distance bed slope shows a fluctuating decreasing trend, whilst hydraulic radius decreases sharply and w:d ratio increases rapidly.

Table 4.15 Geomorphic reaches for Gavins Point Reach.

GR (1960 RM)	Criteria
GR 1 (811-796)	There is an abrupt planform change of direction at about RM 796; bed slope fluctuates but energy slope and w:d ratio show a steady increase from RM 806-RM 797 and RM 806-RM 796, respectively; velocity decreases steadily to RM 796 while hydraulic radius decreases by a large amount to this point; conveyance also decreases significantly to RM 797.
GR 2 (796-776.2)	There is a south-east-south-east step-like progression of the planform in this reach that may be due to the presence of erosion-resistant materials (possibly Dakota Sandstone, this needs field verification) in the left bank; there is a decreased rate of increase in the energy slope from RM 797-RM 775 with a major downwards fluctuation around RM 777.5; there is also a decreased rate of increase in the w:d ratio from RM 796-RM 777; both conveyance and hydraulic radius show a sharply decreased rate of increase throughout this reach.
GR 3 (776.2-764.7)	The river appears to deflect off right bank bluffs from RM 776.3-RM 775.3, before gradually arcing back southwards towards the bluff line that re-commences along the right bank at RM 764.7. As in the previous reach this pattern may be aided by the presence of erosion resistant material (Dakota Sandstone?) along the left bank from approximately RM 767-RM 766. The presence and type of resistant material needs field verification; most of the hydraulic variables maintain fairly constant values in this reach.
GR 4 (764.7-753)	This reach is largely controlled by channel impingement on two sections of right bank bluff line, from RM 764.7-RM 762 and RM753.9 to beyond RM 751. Again, it is possible that erosion-resistant Dakota Sandstone is exerting a controlling influence in the left bank centered at about RM 758; w:d ratio decreases from RM 766.5-RM 756; hydraulic radius increases steadily through the reach while conveyance increases from RM 766-RM 756.

4.9.3. The Brice Classification.

The Brice Classification describes the morphology of rivers or sections of rivers additively in terms of their degree and character of sinuosity, braiding, and anabranching. Each of these three aspects of planform is assigned a number and letter code for the degree and character, respectively, such that each reach can be described by a six letter code. For example, a river section assigned the code 1D 2B 3C would be described as: 1D = having a sinuosity between 1 and 1.05 and be single phase, wider at bends with chutes common; 2B = between 35% and 65% braided with mostly bars and islands; and 3C = have >65% anabranching with split channel, sub-parallel anabranches. A total of 3,120 river types can be identified in this way (Brice 1975).

The system was developed based on the morphological characteristics that were observed from aerial photographs of about 250 river reaches, mostly within the United States but from other parts of the world also, and occurring in climates ranging from arctic to equatorial. In addition to the photographs, large-scale topographic maps, and gauging station data for 200 reaches were used to develop the classification (Brice 1975). A detailed description of the Brice Classifications for each of the four study reaches is shown in Appendix F on the data supplement CD ROM.

4.10. Relationship Between Width and Bars and Islands

An analysis was conducted to determine the relationship between channel width and the presence of bars and islands. The first step in this analysis was to measure the channel width at

0.8-km increments along each of the four study reaches during two time periods using the 1998 orthophotos and aerial photography from the 1980s. At each 0.8-km increment, the photography was examined for the presence or absence of bars and islands. Bars were identified as features which were predominately devoid of visible vegetation, while those features which had a significant vegetative cover were classified as islands. At each location one of three classifications were identified: (1) no bars or islands were present; (2) the presence of bars was visible; or (3) the presence of islands was visible. Using these data, a cumulative distribution rating each classification to channel width was developed. A typical curve for the Gavins Point Reach is shown in Figure 4.10. Box and whisker plots were also developed showing the range from 25% to 75%, the median value, and the maximum and minimum values.

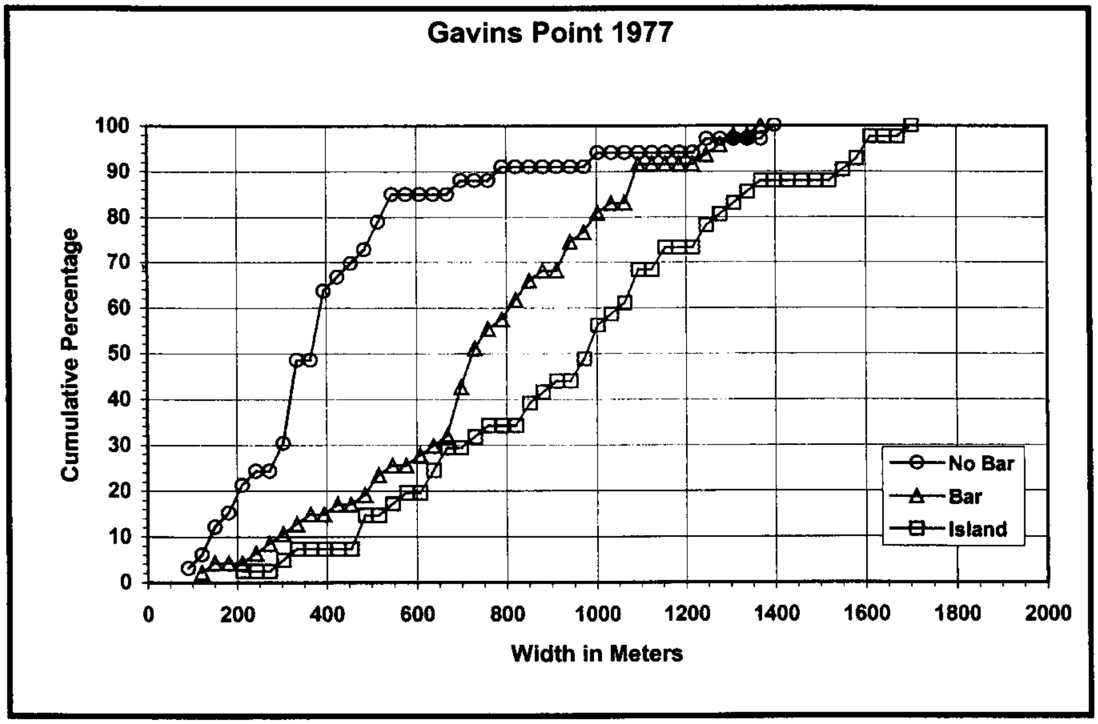


Figure 4.10 Cumulative distribution of channel width and occurrence of bars and islands for 1977 for the Gavins Point Reach.

4.11. Relationships Between Bar and Island Density and Bank Stabilization

An analysis was conducted to examine the potential impact of bank stabilization on bar and island density. To accomplish this, the surface area and density (hectars/kilometer) of all bars and islands were measured using aerial photography from three different time periods in each study reach. The first two time periods were obtained from Pokrefke *et al.* (1998). The most recent calculations were taken from the 1998 orthophotos. Table 4.16 shows the dates of photography for each reach as well as the average discharge at the time of the photography. As shown in Table 4.16, the discharges are similar for all three time periods for the Fort Peck and Fort Randall Reaches. However, for the Gavins Point and Garrison Reaches, the discharges are much greater in the most recent period than in the two previous periods. The bar and island density data from the 1998 orthophotos were determined on 8.0-km increments for each study reach. Pokrefke *et al.*'s reaches were of varying lengths ranging from about 8.0 km up to 32.20 km. For comparison, the 1998 data were combined to match Pokrefke *et al.*'s reaches as closely as possible. In an attempt to determine if there was some relationship between extent of bank stabilization and bar and island density, the percent of bank line that was stabilized in each reach was calculated. This was determined by measuring the length of bank stabilization in each reach and dividing it by the total length of bank line in the reach. For instance, if there were 2 km of stabilization on the left bank and 3 km on the right bank and the total length of the left and right banks was 20 km, then the percentage of stabilized bank line in that reach would be 25%. The left and right bank percentages were also calculated separately.

An attempt was made to determine if a relationship exists between Brice classes and bar density response to revetment construction. The Brice class may be a way of predicting sensitivity to change. However, to verify this it would be necessary to establish Brice classes prior to revetment construction and compare these results to post revetment Brice classes. Based on the available data no definite relationship could be obtained. This was not further pursued in the main analysis.

Table 4.16 Dates of aerial photography and average discharge at the time of photography for each reach.

Reach	Date of Aerial Photography	Discharge (m^3/sec)
Fort Peck	16 August 1974	346
	25 to 26 October 1990	224
	2 September 1998	309
Garrison	10 October 1976	379
	25 October 1990	292
	5 August 1997	1,416
Fort Randall	17 October 1976	1,076
	4 May 1994	835
	28 August 1998	801
	29 August 1998	818
Gavins Point	6 June 1981	906
	5 May 1994	867
	8 August 1997	1,827
	21 August 1997	1,844

4.12. Bank Erosion Calculations

For each of the four Missouri River reaches, the areas of active erosion were defined based on a interpretation of bank lines from aerial photography obtained from the Omaha District, USACE. To accomplish this, approximately 150 aerial photos were scanned and rectified using the 1998 color-infrared (CIR) orthophotos as a base. The rectified images were displayed as a mosaic and the bank line was delineated using stereoscopic display of the photos and on-screen digitizing techniques. The dates of the earlier black and white photography analyzed for each reach are as follows: Gavins Point (1977), Garrison (1980), Fort Randall (1976), and Fort Peck (1983). Calculation of bank erosion by 1.6 km segments was accomplished by comparing bank lines from the earlier (black and white) photos with the 1998 CIR photos. These results were placed in an Excel spreadsheet showing the acreage lost to erosion and gained by deposition by river mile for both the left and right banks in each of the four study reaches.

Next it was necessary to estimate the bank heights for the reach. Left and right bank heights were assigned to each river mile based on observations from the 1999 reconnaissance trip and consideration of available cross-sectional data. Estimates were also made to account for the portion of the bank that was under water at the time of the boat trip. This resulted in adding 1.5 m to the observed bank heights in the Gavins Point, Garrison, and Fort Peck Reaches. No adjustment was deemed necessary in the Fort Randall Reach due to the low-water condition at the time of the boat trip. These bank heights were then multiplied by the bank erosion values calculated above to produce the total volume of material eroded. To obtain an average annual volume of material supplied from bank erosion, the bank erosion volumes were divided by the number of years between photography. This produced values for bank erosion in cubic meters per year.

The bank erosion volumes calculated above reflect the total amount of bank material eroded on an annual basis. However, to assess the impact of this erosion on the island and bar morphology it was necessary to segregate the data based on grain size. To accomplish this, it was first necessary to develop representative bank gradation curves. Each geomorphic reach was evaluated separately and representative bank gradation curves were selected for each GR. Generally, one or two curves were found to be adequate to represent each GR. Combining the volume calculations with the gradation data, the total volume of bank material eroded by grain size was determined. This allows for the calculation of the annual volume of material eroded for any selected grain size.

4.13. Sediment Budget and Bank Contributions

In order to determine the impacts of potential bank stabilization on bar morphology it is necessary to calculate a sediment budget by size fraction for each reach. Once the total sediment load is determined for a reach, the percent of this load derived from bank caving can be calculated. There are several ways that a sediment budget can be developed; however, the inherent uncertainty in these approaches in a data-limited system such as the Missouri River must be recognized. One method is to use measured suspended sediment data to derive the total sediment load for a reach. To accomplish this, there must be sufficient gauging stations to represent the reaches, and grain size analyses must have been performed on the suspended sediment samples. Neither of these conditions were met on the Missouri River reaches. Another limitation of this approach is that the unmeasured load, which can contain a significant portion of the bed material load, must be calculated and added to the measured load to obtain the total load. Also, even under ideal conditions, the amount of scatter on measured suspended sediment curves is extreme, usually covering at least one log cycle. For these reasons, the use of measured suspended sediment data as a means of developing the sediment budget was not feasible. Another way to calculate the sediment budget is to use sediment transport functions to calculate a sediment transport rating curve and then combine this curve with a flow duration curve to develop the annual sediment transport for the reach. As with the measured data, there is extreme variability between the results obtained with various sediment transport functions. For this reason, this approach was not adopted. A variation of this approach would be to set up a one-dimensional sediment transport model for the study reaches and incorporate the bank caving volumes into the model as point sources. This approach was seriously considered, but preliminary evaluations indicated that the level of uncertainty would be no better than with the other methods, so that the extensive modeling effort would not be warranted. For this study, the method used to develop the sediment budget was to utilize the extensive record of measured cross-sectional and planform data for the actual study reaches. For this report, this approach will be referred to as the "ERDC Budget."

The first step in this procedure was to determine the size of material that comprises the bed and habitat bars in the study reach. For each study reach the gradation curves for the bed and habitat bars were examined to determine the appropriate size material to use in the sediment budget calculations. The approach used was to determine the lower limit size of material that was found in appreciable quantities in the bed and habitat bars. The D_{10} values for the habitat bars was selected to represent the discriminator between bed material and wash load in the study reach. Material finer than this can be considered as wash load. Table 4.17 shows the results of the gradation analysis for each study reach. As shown in Table 4.17, the D_{10} values for the bed and habitat bars are similar with the bed being slightly coarser.

Table 4.17 Bed and habitat bar D_{10} gradation values for each study reach.

Reach	Habitat Bar Average D_{10} (mm)	Bed Average D_{10} (mm)	Representative Bed Material Size (mm)
Fort Peck	0.16	0.21	0.16
Garrison	0.14	0.18	0.14
Fort Randall	0.16	0.21	0.16
Gavins Point	0.20	0.23	0.20

The next step was to estimate the total bed material load in each geomorphic reach and then determine what percent of this load was derived from bank caving. To do this it was necessary to develop a sediment budget for each geomorphic reach. In order to accomplish this, the sediment sources and sinks had to be calculated for each geomorphic reach using cross-sectional and planform data from different time periods. Sediment sources within a reach included the sediment inflow from the upstream reach, and sediment eroded from the banks and the bed. Sediment from tributaries is also a potential sediment source but was not included because of the limited availability of data, and the fact that the major tributaries that could provide a significant contribution of sediment all enter at the downstream ends of the study reaches. Sediment sinks included sediment deposited either on the channel bed or banks. Pokrefke *et al.* (1998) conducted a detailed analysis of cross-sectional data during different time periods between the 1960s and 1985 and produced a tabulation of volumetric changes in the bed and banks for all four study reaches. The results are shown in Tables 4.18 through 4.21. Using the Gavins Point data as an example, the sediment budget procedure can be illustrated (Table 4.22). First the reach is divided into geomorphic reaches. Reach 1 in the Gavins Point reach extends from the dam (RM 811) downstream to RM 796. Based on the assumption that no bed material load is entering the reach from the dam, the only sources of sediment in this reach are derived from bed and bank erosion. Using the procedure described in Section 4.12, the annual supply of sediment from bank erosion was calculated at each river mile for both the left and right banks. The lower limit size of bed material for the Gavins Point Reach was determined to be 0.2 mm. Therefore, the total annual volume of material greater than 0.2 mm supplied from the banks was calculated. As indicated in Table 4.22, the annual volume of material greater than 0.2 mm supplied from the banks in GR 1 is 192,289 m^3. The next source of sediment in this reach is the material derived from the erosion of the bed. The annual bed erosion volume, (obtained from Table 4.21) in GR 1 was 343,540 m^3. Next, the sediment sinks were determined from Table 4.21. As shown in Table 4.22, 61,978 m^3/yr was deposited along the banks, and 10,835 m^3/yr was deposited on the bed in GR 1. Subtracting these sinks from the sources produces a total bed material load at the downstream limit of the reach of 463,017 m^3/yr. The same process is repeated for all reaches with the sediment load from the upstream reach being an input to the next reach downstream. For instance, the 463,017 m^3/yr from GR 1 would be the upstream sediment supply to GR 2 (Table 4.22).

Table 4.18. Fort Peck Reach bed and bank erosion/deposition (from Pokrefke *et al.* 1998). Negative values indicate erosion, positive values indicate deposition.

	Erosion/Deposition Rate (m^3/yr)					
	Pokrefke *et al.* (1998) Data (1955-1966)			Pokrefke *et al.* (1998) Data (1968-1978)		
1960 RM	**Left Bank**	**Right Bank**	**Bed**	**Left Bank**	**Right Bank**	**Bed**
1770.0	0	0	0	0	0	0
1769.0	-353	1,019	-2,080	-1,744	-386	-473
1767.7	-9,241	-3,110	-1,467	-3,353	-3,110	3,790
1766.3	0	-1,922	-2,969	0	-1,605	-5,006
1765.1	685	-12,429	-734	374	-4,635	-10,735
1763.9	1,517	-33	-8,351	209	239	-5,741
1761.4	-11,383	9,005	-2,820	-7,226	2,835	-51,395
1759.2	13,396	-419	-9,360	-905	-18,475	-9,594
1757.3	-1,110	-181	-28,356	-1,136	6,889	-13,257
1754.3	-24,466	-5,953	-72,745	-4,373	11,213	39,135
1751.0	3,902	-4,799	-30,007	-2,960	-1,192	-46,749
1747.8	-20,356	-913	696	-3,269	33,850	4,146
1745.8	2,120	-6,497	-60,784	-20,334	-1,969	-19,462

Table 4.18 (continued)

1960 RM	Erosion/Deposition Rate (m^3/yr)					
	Pokrefke *et al.* (1998) Data (1955-1966)			Pokrefke *et al.* (1998) Data (1968-1978)		
	Left Bank	Right Bank	Bed	Left Bank	Right Bank	Bed
1744.0	-196	-8,196	-1,003	606	-6,751	-13,793
1741.2	-37,774	-13,100	29,982	19,396	-15,965	7,877
1736.1	-26,770	-8,237	82,231	25,105	-26,867	-162,208
1733.8	-7,634	-20,089	58,326	-7,621	-20,105	2,906
1731.7	1,420	9,119	40,481	-7,421	10,729	-27,212
1728.1	-23,728	-55,608	-22,515	-37,808	-25,354	10,987
1724.5	-109,558	-1,174	38,362	-67,146	1,435	-9,419
1723.9	-1,452	0	0	-1,233	0	-1,757
1720.0	-106	-73,259	-64,300	1,992	-128,331	4,519
1715.5	30,705	-95,172	24,405	-12,167	-59,600	-5,102
1712.1	-10,629	-1,571	14,696	-11,014	-381	22,875
1707.7	0	0	0	0	0	0
1707.6	-1,927	1,450	3,556	-506	1,209	1,378
1707.5	0	0	0	0	0	0
1700.5	-7,707	-73,356	13,014	-31,049	-169,199	-34,101
1695.0	-11,288	2,018	-12,933	-3,769	19,804	-37,827
1687.5	-129,261	1,937	204,697	-93	-23,081	-213,710
1682.5	-60,961	-2,650	-1,563	-7,413	-1,620	31,335
1674.8	-69,808	-123,916	229,203	-162,134	10,073	-74,256
1669.5	-31,265	6,051	-54,821	-30,574	-27,669	23,310
1661.9	-138,310	-6,782	155,162	86,752	3,956	-96,360
1661.7	0	0	0	0	0	0
1653.3	-8,791	5,252	-4,795	4,919	19,048	-37,468
1647.2	27,444	9,535	-156,289	-78,282	1,292	-380
1643.4	671	-26,806	-25,257	-16,713	21,069	-5,918
1638.8	-10,629	5,502	-17,882	28,141	-3,439	-745
1631.3	0	0	0	0	0	0
1624.9	86,380	-136,486	-47,061	-92,578	109,882	-52,868
1623.3	0	0	0	0	0	0
1620.9	1,267	-12,572	37,910	-11,256	8,636	-12,269
1616.8	-30,039	-17,094	-15,213	-126,927	22,819	54,665
1612.0	17,159	-42,277	82,792	-5,622	-89,887	-23,862
1607.7	-29,807	2,981	-19,170	-46,450	536	185,800
1603.4	-200,937	8,416	111,807	-23,412	30,967	-9,322
1599.0	-30,501	-28,647	19,317	2,851	-8,717	-4,989

Table 4.19 Garrison Reach bed and bank erosion/deposition (from Pokrefke *et al.* 1998). Negative values indicate erosion, positive values indicate deposition.

	Erosion/Deposition Rate (m^3/yr)					
	Pokrefke *et al.* (1998) Data (1956/58-1976)			Pokrefke *et al.* (1998) Data (1976-1985)		
1960 RM	Left Bank	Right Bank	Bed	Left Bank	Right Bank	Bed
1388.3	0	0	0	0	0	0
1387.1	1,722	-1,731	-62,141	-1,635	1,894	-35,464
1386.0	-4,769	-41,856	-26,216	-439	-6,103	-2,302
1385.0	-1,961	336	-53,698	50	-1,379	-15,450
1383.4	-9,485	-24,831	-97,985	-12,546	-5,794	-36,867
1382.3	-3,906	-6,463	-69,535	-1,919	2,522	-38,247
1381.4	794	444	-35,839	-867	-4,022	-673
1380.6	-14,903	-53,873	-24,179	-8,094	-63,354	7,389
1379.7	-65,673	-7,986	-22,337	-92,444	-7,012	15,714
1378.9	-19,572	-1,411	-25,377	-37,311	-79	-7,651
1378.5	-2,347	3,889	1,131	-2,656	3,019	7,302
1377.4	-19,333	-9,553	-20,421	-19,592	-8,149	4,354
1376.5	-3,795	-54,296	-11,337	-8,911	-42,252	-6,160
1375.7	-35,333	-7,033	-38,000	-173	0	0
1374.9	-981	-8,498	-27,756	-5,396	-5,675	-85,149
1374.4	-3,499	-13,636	-28,759	-5,675	-17,460	-282
1373.8	-14,304	-15,170	-22,234	-11,213	2,223	-41,126
1372.3	-4,149	3,902	-54,161	-7,376	0	-3,538
1371.5	341	-3,020	-65,726	1,023	306	-52,217
1370.5	-3,125	1,682	-92,212	0	0	-17
1369.1	-24,344	1,172	-59,195	-8,047	279	-149,011
1367.6	-2,422	359	-163,134	-16,073	324	110,565
1366.5	-17,885	-14,111	-62,562	-17,232	-17,707	31,723
1365.0	-23,055	7,132	-120,848	8,697	1,969	-76,326
1364.1	-27,599	-36,628	-28,070	-5,233	14,578	-3,633
1362.7	-8,582	-17,311	-57,521	11,838	-58,214	-21,002
1361.3	-11,209	-13,679	-78,589	47,818	-58,818	114,637
1358.5	0	0	0	0	0	0
1356.2	-656	-25,471	-180,873	-9,785	44,784	-27,822
1353.8	-1,399	-24,096	-76,593	-10,566	-94,771	-23,284
1351.7	-48,164	-40,519	-33,046	44,375	-100,229	-125,800
1349.2	-200,048	-26,613	135,963	81,900	-42,570	-168,784
1348.3	-15,002	-6,439	-55,499	-12,815	-1,493	-68,507
1344.8	-33,629	9,217	-4,564	8,173	1,545	-24,346
1343.3	2,489	-86,714	25,298	-68,377	35,783	28,507
1341.4	-1,378	-63,761	-67,525	-3,535	32,732	-46,588
1339.8	-9,987	-54,722	11,554	930	-60,922	27,696
1338.2	-43,155	-383	-21,063	213	1,967	-92,685
1337.2	-3,162	15	-5,607	116	-122,650	42,445
1336.2	-2,385	-1,682	-32,056	-9,552	-4,037	27,178

Table 4.20 Fort Randall Reach bed and bank erosion/deposition (from Pokrefke *et al.* 1998). Negative values indicate erosion, positive values indicate deposition.

	Erosion/Deposition Rate (m^3/yr)					
	Pokrefke *et al.* (1998) Data (1954-1976)			Pokrefke *et al.* (1998) Data (1975-1985)		
1960 RM	Left Bank	Right Bank	Bed	Left Bank	Right Bank	Bed
879.3	0	0	0	0	0	0
878.6	-3,902	-4,027	4,421	-18,284	-4,553	-17,447
877.5	-5,067	-1,065	-59,575	-3,798	-470	-12,993
876.7	5,827	-3,605	-44,740	-1,481	-575	-7,940
876.4	513	-4,146	-16,062	53	-2,424	-5,395
875.8	-18,604	-6,561	-70,399	-2,704	-26	-46,135
875.2	0	0	0	0	0	0
874.8	649	-10,130	-37,116	-1,045	-3,548	-5,459
872.0	-379	-22,866	-114,706	977	-13,675	26,673
871.8	-238	-5,334	-9,209	-68	2,610	-2,943
870.4	-1,067	11,971	-65,337	-1,924	8,672	-13,626
869.8	-3,477	3,554	-27,835	-564	-4,618	-10,739
868.0	-265,151	13,008	55,042	39,676	-40,048	-25,246
867.0	-20,020	-15,428	-68,448	-12,986	456	15,222
865.1	-9,699	676	-57,194	-44,857	460	-45,966
863.5	-2,438	-36,703	17,087	262	-29,265	-86,370
862.6	5,802	-8,926	-14,770	1,051	-4,082	-29,597
861.5	0	0	0	0	0	0
859.5	-2,179	-11,947	-40,796	-1,680	-4,955	22,128
856.3	706	-3,759	-40,599	570	1,914	-52,948
854.7	-2,905	-14,684	13,541	2,677	-11,881	-74,136
853.1	-49,393	-24,526	-11,676	5,946	-2,893	1,185
850.8	-72,067	-868	78,143	4,765	-884	-100,839
849.0	3,306	-53,427	95,180	-3,627	20,902	-38,049
848.1	3,294	1,397	23,555	20,184	372	11,233
847.5	-11,085	-3,370	22,756	1,337	-2,999	9,872
845.1	-24,725	22,282	80,805	-75,679	21,274	54,628
844.2	788	-12,405	26,714	775	-11,880	59,066

Table 4.21 Gavins Point Reach bed and bank erosion/deposition (from Pokrefke *et al.* 1998). Negative values indicate erosion, positive values indicate deposition.

	Erosion/Deposition Rate (m^3/yr)					
	Pokrefke *et al.* (1998) Data (1960-1974)			Pokrefke *et al.* (1998) Data (1974-1986)		
1960 RM	**Left Bank**	**Right Bank**	**Bed**	**Left Bank**	**Right Bank**	**Bed**
810.7	0	0	0	0	0	0
809.9	-5,331	-1,956	-35,772	-632	137	-18,719
809.2	-643	-568	-44,204	0	-867	-2,848
808.6	-1,519	-1,153	-39,670	-3,435	-948	-2,371
808.0	0	-10,445	-64,192	0	820	-15,411
807.0	-112,476	0	-12,698	-33,961	0	9,046
806.2	-3,247	-325	-69,365	-2,580	0	-29,458
806.0	-70	45	-8,606	-56	62	-5,718
805.8	0	0	0	0	0	0
805.4	-692	-743	-21,714	-568	-1,294	-13,217
804.5	-34,746	-19,694	-9,227	682	-34,746	-44,809
803.9	-23,106	-449	-26,605	-9,214	320	-23,004
802.0	-60,548	-316,723	64,505	22,340	-185,257	-12,641
801.1	-12,533	-129,823	-7,113	29,863	-11,322	1,788
800.0	-55,648	2,537	-27,101	18,432	4,041	-62,273
798.8	-18,916	-13,174	-36,755	-22,388	-31,910	-44,969
797.9	-1,653	-8,785	-40,090	-221	-433	-49,105
797.0	-70,520	-103,161	41,061	15,138	-87,561	-18,964
795.6	-32,205	-98,320	-48,726	3,095	-187,310	61,898
794.5	-10,843	-2,021	-68,464	-47,260	905	-37,169
793.3	1,845	-12,918	-20,466	12,046	14,661	-47,930
792.5	-38,711	-2,102	19,206	5,545	-10,398	-31,466
790.3	-23,307	-25,069	-38,179	-16,164	-148,135	-38,273
789.2	-24,717	-787	-160,376	-10,385	0	-73,680
787.7	-20,296	7,064	5,014	-31,990	-9,163	-80,000
786.9	-1,059	-2,674	-8,655	-8,783	-85	-25,896
786.0	-33,448	-25,807	-10,986	-40,417	-13,908	-1,836
784.5	-2,275	-23,484	-12,399	-34,586	-88,410	7,769
782.2	-27,805	1,474	-114,144	-11,716	-2,505	-56,396
780.2	-19,757	-105,706	39,706	-20,206	-270,982	-104,125
778.6	-42,598	-101,293	-146,523	-69,767	-13,294	25,665
777.0	-318,403	-64,795	58,780	-74,603	59,293	-72,416
775.9	-1,645	-39,753	-23,859	0	-6,226	6,567
773.9	983	-79,221	-39,899	-491	-282,964	48,271
771.4	-305,594	14,604	52,543	61,194	-18,315	-321,079
769.0	-17,531	-140,662	-141,405	-15,763	-13,712	-40,497
762.6	-3,486	-56,388	-319,872	2,256	-21,598	-311,807
761.7	0	0	0	-51,710	-92,050	8,679
758.1	-216,606	-732,900	-42,483	159,590	-205,918	97,154
756.0	-64,119	-98,185	-43,262	-259,368	-3,342	-44,944
753.1	0	-898	-536,750	0	2,478	-232,682

Table 4.22 Gavins Point sediment budget.

Geomorphic Reaches (RM)	Erosion		Deposition		Net Sediment Transport from Erosion & Deposition (m^3/yr)	Upstream Sediment Supply (m^3/yr)	Sediment Transport Budget (m^3/y)r
	Bank (1977-1998) (m^3/yr)	Bed (1974-1986) (m^3/yr)	Bank (1974-1986) m^3/yr)	Bed (1974-1986) (m^3/yr)			
GR 1 (811.0 - 796.0)	-192,290	-343,540	61,978	10,835	-463,017	0	-463,017
GR 2 (795.0 - 776.2)	-356,272	-569,242	95,554	95,341	-734,619	-463,017	-1,197,636
GR 3 (775.0 - 764.7)	-639,185	-361,611	61,200	54,843	-884,753	-1,197,636	-2,082,388
GR 4 (763.0 - 752.0)	-411,151	-589,490	164,340	105,843	-730,458	-2,082,388	-2,812,846
Total Transport (811.0 - 752.0)	-1,598,898	-1,863,883	383,072	266,863	-2,812,846	---	---

4.14. Effects of Bank Stabilization

Once the total bed material budget is calculated for a given reach the percentage of the load comprised by the bank caving was calculated by dividing the bank erosion value (column 2, Table 4.22) by the sediment transport budget value (last column, Table 4.22). For instance, the bank contribution for GR 1 in the Gavins Point Reach is 42% (192,290 divided by 463,017). Next an attempt was made to estimate the percent reduction in bank material supply resulting from various stabilization schemes ranging from stabilizing 10%, 20%, etc. up to 100% of the eroding areas in the reach. Table 4.23 shows an example from the Gavins Point Reach. As shown in Table 4.23, if 10% of the eroding areas were stabilized in GR 1, then there would be a 4% reduction in the supply of bed material sized sediment in this reach. Since the bank material comprises 42% of the total bed material load in GR 1, stabilizing 100% of the eroding areas would result in a 42% reduction in the supply of bed material to the reach. By fixing the total bed material transport and calculating a reduced contribution from the banks, it is assumed that the channel will make up this deficit due to the reduced bank supply by scouring additional material from the channel bed, bars, islands or unprotected banks.

Table 4.23 Bank stabilization impact on the Gavins Point Reach.

Gavins Point budget with >0.20 mm bed material size.

Revetment Percentage	Geomorphic Reaches				Reach Average Reduction of Bank Contribution RM 811 – RM 753.9
	Reduction of Bank Contribution GR 1 RM 811 – RM 796	Reduction of Bank Contribution GR 2 RM 796 – RM 776.2	Reduction of Bank Contribution GR 3 RM 776.2 – RM 764.2	Reduction of Bank Contribution GR 4 RM 764.2 – RM 753.9	
10	4%	3%	3%	1%	2%
20	8%	6%	6%	3%	5%
30	12%	9%	9%	4%	7%
40	17%	12%	12%	6%	10%
50	21%	15%	15%	7%	12%
60	25%	18%	18%	9%	15%
70	29%	21%	21%	10%	17%
80	33%	24%	25%	12%	20%
90	37%	27%	28%	13%	22%
100	42%	30%	31%	15%	24%

4.15. GIS Development

4.15.1. Introduction.

Global Position System (GPS) and Geographic Information System (GIS) tools were utilized during this study for the collection and analysis of spatially referenced data. The products of these efforts include:

- Field data locations;
- Boat-based and aircraft-based geo-referenced videos;
- Bank line delineation;
- An emergent feature classification; and
- A land use classification.

Each of these products represent a tremendous cooperative team effort by members of the Omaha District GIS and field teams, the ERDC-EL GIS team, and the field crew from CSU. The first four items were used in the geomorphological assessment related to bank stabilization. The final item, land use classification, was completed at the request of the Omaha District, and not used in this analysis. The field data locations and geo-referenced videos are essentially raw data that are available for incorporating into GIS layers. The bank line delineations, emergent feature classification, and land use classification already exist as GIS layers and are available on CDROM and is available upon request from the Omaha District.

4.15.2. Field Data Locations.

A GPS unit was used to locate most of the 312 sites where sediment samples were collected during the field investigation. The field team was provided with aerial mosaic maps of the four river reaches with sampling sites delineated based on the boat reconnaissance trip and data from the literature. Each sample site was designated as a 'waypoint' (WPT). A GPS unit was used to record the location of each waypoint and downloaded as an ASCII file. Each waypoint was also marked on aerial mosaics in the field. The ASCII files containing the GPS coordinates of each waypoint were given to the Omaha District in spreadsheet form. The district will also receive the marked aerial mosaics for cross-referencing the data before a GIS layer is completed.

4.15.3. Boat-based and Aircraft-based Geo-referenced Videos.

For the boat mission, the Environmental Laboratory engineer, Charles Hahn, deployed two Image Data Aquisition Systems (IDAS) to image each bank and shoreline during the initial boat reconnaissance of the Missouri River from Fort Peck Dam to Ponca State Park during the period 1-9 June 1999. The IDAS incorporates a digital compass, gyroscope, and pressure altimeter with the cameras and the GPS equipment to record the camera's viewing geometry. This information is then processed with the position information from the GPS and an approximate position is calculated for the center Field-of-View of the image. For each river reach except the Fort Randall Reach, the boat traveled downstream, so the port camera imaged the left descending bank and the starboard camera imaged the right descending bank. Each system was comprised of a S-video camera, an electronic laser rangefinder, time-code generator, a video recorder, a video monitor, and a GPS receiver. Video cameras operated continuously (except when samples were being collected or the boat stopped for any other reason). One stretch of river was not recorded (approximately 65.9 km upriver from the Hwy 16 Bridge at Culbertson, Montana) due to extreme weather conditions in the area (heavy rains). The tape library is comprised of 40 tapes; 20 tapes for each shoreline. The GPS time and position have been recorded onto the video imagery so that the boat position can be determined without the use of the specialized encoder/decoder hardware. However, the tapes used were of the Super-VHS (SVHS) variety for archival quality and require a SVHS player/recorder for proper viewing. It is possible to copy the SVHS format from a SVHS machine to a standard machine.

The aircraft-based video data for the Missouri River shorelines were collected during the period 7-11 July 1999. The video tapes were collected using a Cessna 172 aircraft. For this mission the original tapes were recorded in a SVHS mode, however, the decoded copies were recorded in standard VHS mode. The equipment used for this mission was similar to that used during the boat reconnaissance. For this mission, two video cameras were used, one set to image the maximum field of view, while the second set to image a narrow field of view. A laser range-finder was also used to measure the range from the aircraft to the riverbank. The GPS receiver used was a Trimble Navigation Pathfinder Pro-XRS which was set to differentially correct the GPS position real time, using data from the Omni-Star satellite differential correction system. The aircraft was flown at 152.4 m above ground level at a speed of approximately 129.7 km/hr. The aircraft position and universal time code time signal are displayed on the video image. The time is Zulu or Greenwich Mean time.

The tapes and a memorandum with maps detailing the path of the boat and aircraft in the reaches and examples of still frames from the videos were sent to the Omaha District.

4.15.4. Bank Line Delineation.

The main goal of this portion of the project was to characterize the bank line from earlier dates of photography and to compare this bank line with those delineated from 1998 CIR orthophotos. In some areas the 1998 CIR orthophotos did not cover the entire reach. In those cases, bank line was delineated only for the areas covered by the CIR orthophotos. The delineation and calculation of the active erosion areas is discussed in Section 4.12.

Statistics for each reach were computed. Statistics produced from the black and white photos include evaluations of bank line retreat or advance between the two dates (for 8.0-km and 1.6-km segments of the reach), and an analysis of total channel width for each 1.6-km segment of the four reaches. In addition, statistics were produced for the islands that were delineated from the 1998 CIR orthophotos in a previous study.

4.15.5. Emergent Feature Classification.

Emergent features in the in-bank areas of the four Missouri River reaches were defined and characterized from the 1998 digital orthophotos according to the classification scheme utilized in a previous study (Pokrefke *et al.* 1998). The digital orthophotos were displayed at an effective scale of 1:10,000 and island boundaries extracted through a "heads-up" digitizing process. An attribute was attached to each polygon, according to the following classification scheme:

- Island (vegetated)
- Bar (not vegetated)
- Border fill
- Chute fill
- Tributary fill

In order to allow multidate comparisons with data generated during the study cited above, Autocad files from the 1998 study were registered to the GIS database. Since the Autocad files are not referenced to a coordinate system, this involved matching the shoreline (as well as possible) from the older data to the shoreline extracted from the 1998 digital orthophotos. It was determined that the alignment was not of sufficient quality to permit straightforward analysis of bank-line or bar migration rates. For an improved comparative analysis, the historical aerial photos would need to be digitized with the state-of-the-art technology to match more closely the ortho-photo data. This was done for one set of photos as described in the previous section.

In addition, basic statistics from the 1998 classification (number of island polygons, area of each type and total area, density of islands) within the same sub-reaches which were defined in the 1998 study.

4.15.6. Land Use Classification.

The GIS CD ROM contains the results of a land cover/land use mapping project for four Missouri River reaches (Gavins Point, Fort Randall, Garrison, and Fort Peck), representing approximately 608.2 km of the Missouri River.

For each of the four Missouri River study reaches, the area of active bank erosion was defined as a linear feature, based on a manual interpretation of the toe line from 1998 digital CIR orthophotos provided by the Omaha District, USACE. The line was broken into segments and a land use/land cover attribute was assigned to each segment using the classification scheme defined below.

Areal land use/land cover away from the active erosion line was defined by displaying the digital orthophotos at a scale of 1:10,000 and using an on-screen digitizing approach to define polygons. A land use/land cover attribute was attached to each polygon using the same classification as applied to the linear bank line features.

The coverage of the orthophotos limited the analysis, as the entire floodplain was not represented in some areas.

The classification system used, closely follows the classification scheme developed by the U.S. Geological Survey in USGS Professional Paper 964, often referred to as the Anderson Classification. The following Anderson Level I classes were assigned:

1	Urban or Built Up Land	(residential, commercial, recreational)
2	Agriculture	(cropland, orchards, etc.)
3	Rangeland/non-agri. vegetated land	(shrub/brush rangeland, pasture)
4	Forest	
5	Water	
6	Barren/non-vegetated	(beaches, sandy areas, rock, etc.)

For each reach, two GIS data layers were created - one for the land cover/land use and one for the bank line. Complete documentation for the GIS data is supplied within the metadata files.

4.16. Sensitivity Analysis

A potential source of uncertainty in the ERDC Budget is that it relies on two different data sources (planform analyses for the bank erosion estimates and cross-sectional analyses from Pokrefke *et al.* 1998) from slightly different time periods. Therefore, the analysis was also conducted using only the Pokrefke *et al.* (1998) data. The results of the analysis using only the Pokrefke *et al.* (1998) data are shown in Appendix G. This will be referred to as the Pokrefke Budget to distinguish it from the ERDC Budget. Comparison of the results between the two methods reveals that while some differences do exist within individual geomorphic reaches, the overall results are generally comparable. A comparison of the results for the total bed material transport at the downstream end of each reach is shown in Table 4.24. As shown in Table 4.24, the two methods produce almost identical results (within 3%) for the Fort Peck Reach, and are within about 20% of each other for the Garrison, Fort Randall and Gavins Point Reaches. Table 4.25 shows the comparison between the two methods for the reach average percent contribution of bank material to the bed material load. As shown in Table 4.25, the results are generally within a few percent of each other.

Table 4.24 Comparison of annual sediment budget – Pokrefke Budget and ERDC Budget.

Reach	Pokrefke *et al.* Sediment Transport Budget (m^3/yr)	ERDC Sediment Transport Budget (m^3/yr)	Difference (m^3/yr)	Difference in Percent
Fort Peck	-752,763	-732,496	-20,267	3%
Garrison	-1,026,072	-844,221	-181,851	21%
Fort Randall	-472,404	-402,117	-70,287	17%
Gavins Point	-2,353,264	-2,812,846	-459,582	16%

Table 4.25 Comparison of the ERDC and Pokrefke Budgets for the reach average percent contribution of bank material to the bed material load.

Reach	Comparison of the reach average percent contribution of bank material to the bed material load for the ERDC and Pokrefke Budgets.	
	ERDC Budget	Pokrefke Budget
Fort Peck	17%	15%
Garrison	13%	18%
Fort Randall	8%	4%
Gavins Point	24%	19%

Appendix G also contains the sediment budget results calculated for varying bed material sizes ranging from 0.063 mm (the break between sands and silts) up to the actual bed material size selected for the reach. These tables are useful for establishing the sensitivity of the calculations to the selected bed material size. A summary of these results is shown in Table 4.26, which shows the reach average percent contribution of bank material to the bed material load for various bed material sizes. As shown in Table 4.26, even if the bed material size is assumed to be 0.063 mm, the increase in the percent contribution of the bank material to the total bed material load as compared to the results of the ERDC Budget is generally less than about 5%. Thus, the results are not overly sensitive to the selection of the bed material size.

While it is recognized that there may be some uncertainty in the ERDC Budget due to the use of different data sources with different time periods, and the selected bed material size, the results do not appear to be overly sensitive to these factors. Consequently, it is concluded that the results are reasonable, and do provide a good general estimate of the overall sediment budget for each reach. Should the user wish to use the Pokrefke Budget, or an alternative bed material size, instead of the ERDC Budget, the results are provided in Appendix G for this application.

Table 4.26 Reach average percent contribution of bank material to bed material load for different bed material sizes based on the ERDC Budget.

Reach	Reach average percent contribution of bank material to bed material load for different bed material sizes*				
	0.063 mm	0.140 mm	0.160 mm	0.175 mm	0.200 mm
Fort Peck	21%	19%	**17%**	15%	13%
Garrison	14%	**13%**	11%	10%	8%
Fort Randall	12%	10%	**8%**	7%	6%
Gavins Point	32%	30%	28%	26%	**24%**

*numbers in bold represent selected bed material size used in ERDC Budget.

CHAPTER 5

RESULTS

5.1. Fort Peck Reach

5.1.1. General Characteristics of the Fort Peck Reach.

The Fort Peck study reach extends from RM 1766, just downstream of the Fort Peck Dam, to RM 1582 near the confluence with the Yellowstone River (Figure 5.1). This reach is regulated by the Fort Peck Dam, which was constructed by the USACE between 1933 and 1940. The mean daily flow at the Culbertson gauge is about 345 CMS. Bed material in the reach is predominately sand. Outcrops of gravel, cobbles, and dense clay are occasionally observed. Bed material tends to be coarser in the reach immediately downstream of the dam (Simon *et al.* 1999). The channel in this reach exhibits a meandering pattern with occasional straight reaches. The channel width ranges from about 135 m to 850 m with an average width of about 300 m. The energy slope for the Fort Peck Reach, calculated from the HEC-RAS analysis, ranges from about 0.0003 to 0.0005. The most important tributary in this reach is the Yellowstone River, which enters at the downstream boundary of the study area. There are several minor tributaries in this reach such as the Milk River, Poplar River, and Redwater River, but taken together their contribution to the discharge in this reach is generally less than about five percent. Bank heights in this reach generally range from about 3 to 12 m with an average bank height of about 5.5 m. For this study, the Fort Peck Reach was divided into eight GRs. A detailed description of the bank stability in the Fort Peck Reach is provided by Simon *et al.* (1999).

The specific gauge records for the Fort Peck Reach are shown in Appendix C of the data supplement CD ROM. Although there are seven locations on the Missouri River in the Fort Peck Reach where specific gauge data were available, only the gauge near Wolf Point (RM 1701) and Culbertson (RM 1620) had recent data extending through the late 1990s. At the Wolf Point gauge, there was no apparent trend in stages during the past 20 years, which suggests that the channel morphology in this area may be approaching dynamic equilibrium. According to the specific gauge results on the Poplar River, which enters the Missouri River at RM 1678.9, there was a slight aggradational trend during the period 1984 to 1999, which would support the conclusion that the Missouri River in this vicinity is no longer degradational. At the Culbertson gauge, the limited data suggest a very slight degradational change for the low flows (less than 283 CMS) in 1997 and 1998, but this is much too short of a time frame to establish whether this is a real trend or just a short fluctuation. Because of these data limitations it is difficult to draw any definite conclusions from the specific gauge data regarding the recent stability of the reach.

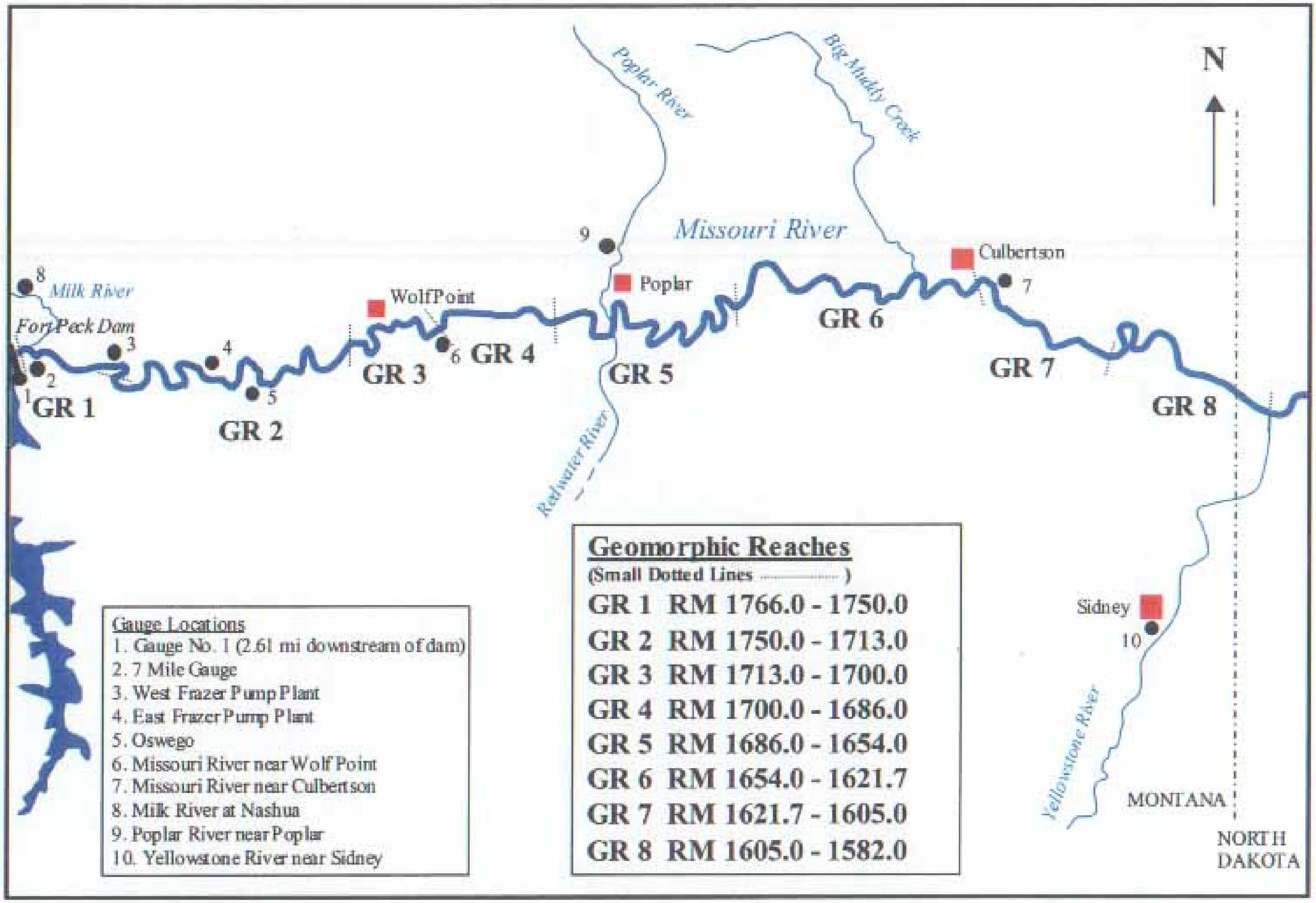


Figure 5.1 Vicinity map for the Fort Peck Reach.

Other studies have investigated the trends in the Fort Peck Reach since the closure of the dam (Dangberg *et al.* 1988a). According to Dangberg *et al.* (1988a) widespread degradation extended downstream to a point between Wolf Point and gauging station No. 6 at RM 1701 (Figure 5.1). Downstream of this location, areas of aggradation were identified. Simon *et al.* (1999) used comparative profiles to show that post-impoundment degradation had been most pronounced in the 112.6 km reach between the dam and about RM 1700. Thus, according to both these results, the area in the vicinity of RM 1700 represents the transition between upstream degradation and downstream aggradation.

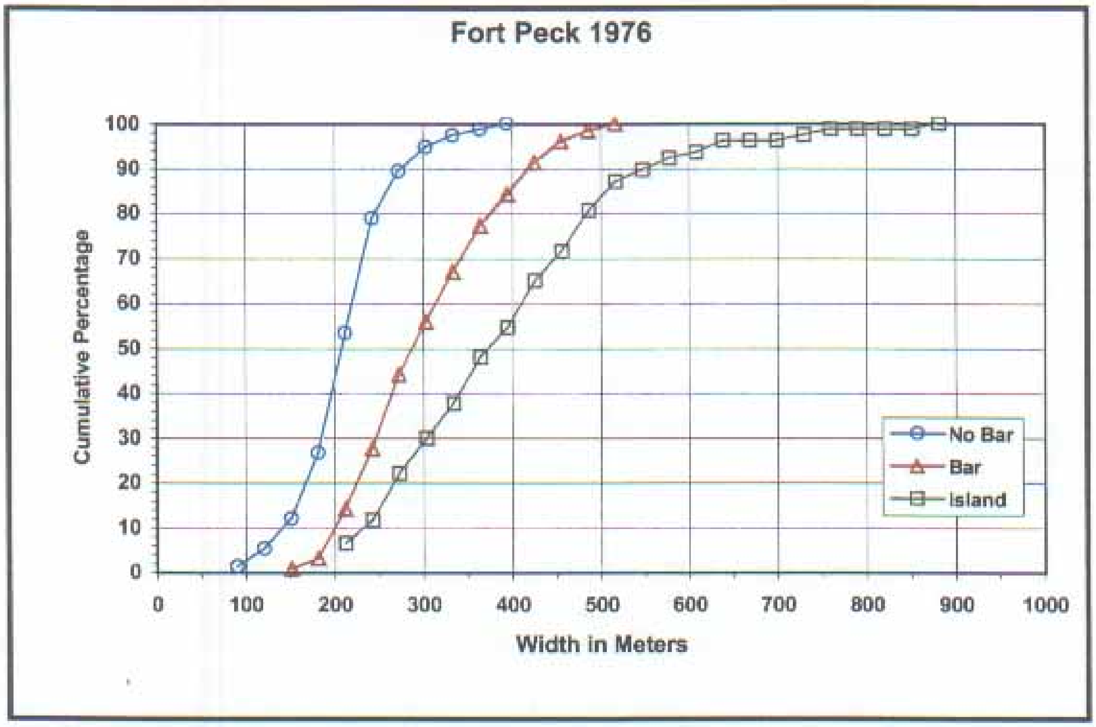
Although it is difficult to establish, with certainty, the existing stability of the Fort Peck Reach, it appears that the upstream portion of the reach between the dam and the vicinity of RM 1700 may be experiencing some degradation, while the downstream reaches are experiencing aggradation. It is also difficult to establish the precise location of the transition area between the degradation and aggradation reaches, but it appears that this transition area occurs between about RM 1700 and RM 1679, near the confluence with the Poplar River.

5.1.2. Relationship Between Channel Width and Bars and Islands.

The cumulative distribution relating channel width and the occurrence of bars and islands for two time periods, 1976 and 1988, is shown in Figure 5.2. Box and whisker plots for the data are shown in Figure 5.3. Although there were some minor differences, the general shape of the curves are similar for the two time periods (Figure 5.2), and the mean, 25% and 75% values were within the same range (Figure 5.3). Figure 5.2 illustrates that reaches with no bars present are much narrower than reaches with bars or islands present. The plots in Figures 5.2 and 5.3 reveal that in 1998 the mean value of channel width for reaches with no bars was about 227 m, while the reaches with bars, and those with islands had mean channel widths of 327 m and 461 m, respectively. Likewise, 75% of the reaches with no bars had channel widths less than about 255 m, while only about 17% of the reaches with bars had a channel widths less than 255 m. Only about 2% of the reaches with islands had channel width less than 255 m. Thus, for the Fort Peck Reach a channel width in the range of about 255 m appears to be a threshold zone below which it is very unlikely that bars will exist. These data suggest a strong relationship between channel width and the presence of bars and islands. Thus, channel width may be a critical factor in the formation of bars and islands in the Fort Peck Reach.

5.1.3. Bar and Island Density Analysis.

The results of the bar and island density analysis for the Fort Peck Reach are shown in Table 5.1. For the 1998 period, there were no data available for downstream of RM 1623.4, therefore, there are no entries for the last three reaches. As shown in Table 4.16, the dates of the aerial photography and the associated discharges were August 16, 1974 (345 CMS), October 25-26, 1990 (224 CMS), and September 2, 1998 (308 CMS). Thus, the discharge range for all three time periods was similar. As shown in Table 5.1, island density values have fluctuated through time, increasing and decreasing with perhaps a very slight increasing trend. In fact, the reach average values have remained essentially unchanged, at between about 8.7 and 9.5 ha/km. The bars have experienced a similar trend to the islands, except that there appears to be a more



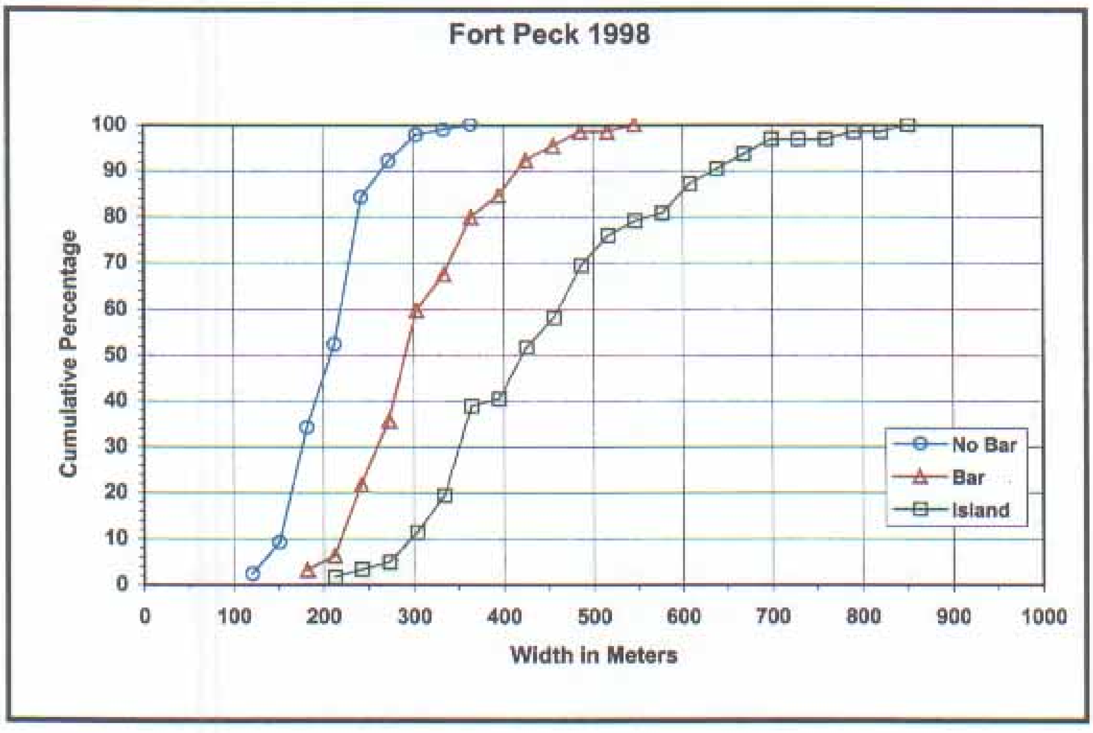
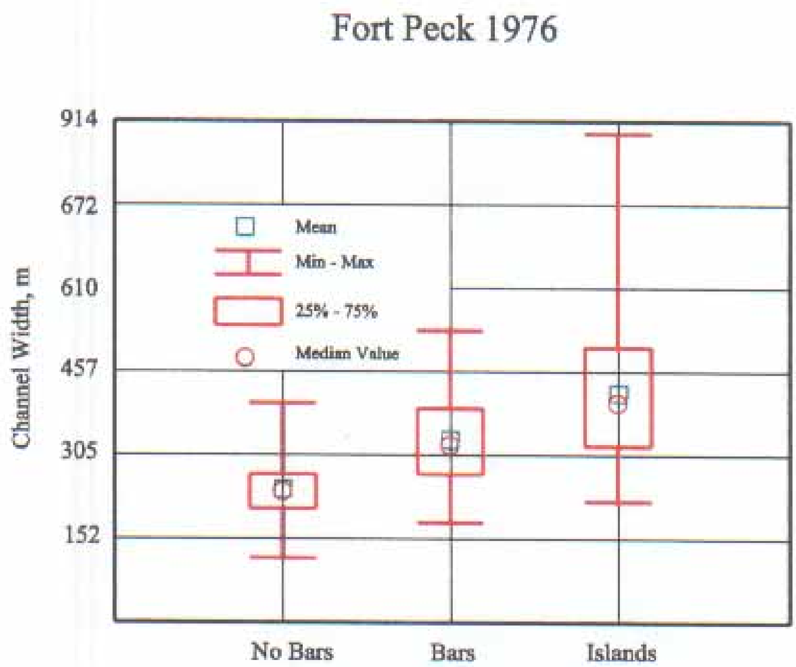


Figure 5.2 **Cumulative distribution of channel width and occurrence of bars and islands 1976 and 1998, for the Fort Peck Reach.**



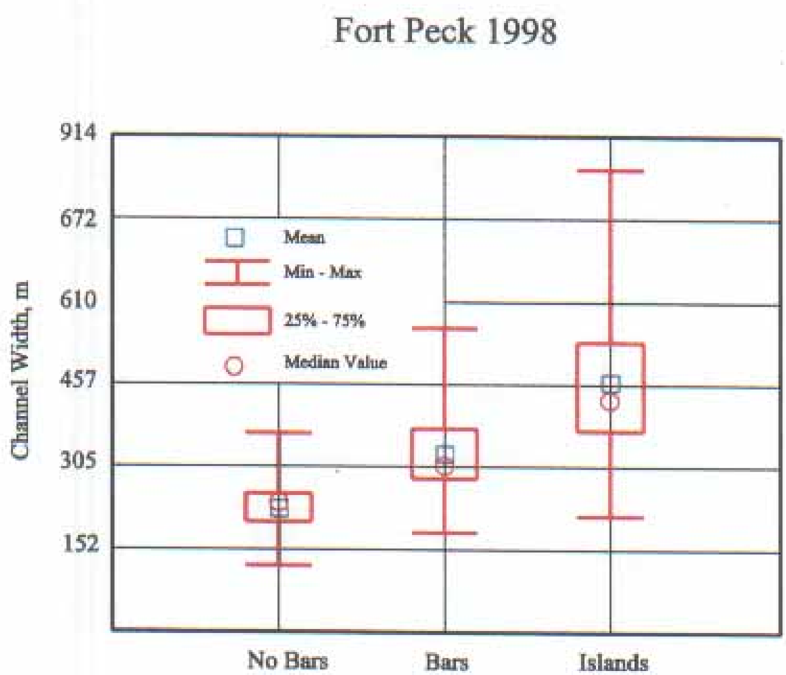


Figure 5.3 **Box and whisker plots displaying the cumulative distribution of channel width and occurrence of bars and islands for 1976 and 1998, for the Fort Peck Reach.**

Table 5.1 Island and sandbar density for the Fort Peck Reach.

Fort Peck Reach, Island and Sandbar Density						
	1960 RM		Reach Length (km)	Density (ha/km)		
	Upstream	Downstream		As of 1974	As of 1990	As of 1998
Islands	1770.7	1763.4	11.7	15.4	19.5	-
	1763.4	1748.4	24.1	2.0	3.1	8.0
	1748.4	1673.4	120.7	-	-	10.1
	1673.4	1668.4	8.0	12.8	2.4	3.2
	1668.4	1658.4	16.1	6.3	9.1	9.0
	1658.4	1653.4	8.0	-	-	10.3
	1653.4	1648.4	8.0	6.3	11.7	7.3
	1648.4	1643.4	8.0	11.2	6.0	6.5
	1643.4	1638.4	8.0	14.8	15.6	18.5
	1638.4	1633.4	8.0	-	-	13.0
	1633.4	1628.4	8.0	4.9	11.7	16.5
	1628.4	1623.4	8.0	14.8	15.7	1.1
	1623.4	1603.0	32.8	6.6	5.8	-
	1603.0	1599.0	6.4	51.0	2.3	-
	1599.0	1596.0	4.8	12.6	22.9	-
	Entire Reach Average			8.7	9.50	9.6
Sandbars	1770.7	1763.4	11.7	0.3	0.3	-
	1763.4	1748.4	24.1	0.1	0.1	0.2
	1748.4	1673.4	120.7	-	-	4.1
	1673.4	1668.4	8.0	2.4	4.0	9.2
	1668.4	1658.4	16.1	1.8	3.1	7.8
	1658.4	1653.4	8.0	-	-	1.1
	1653.4	1648.4	8.0	4.4	5.2	3.8
	1648.4	1643.4	8.0	1.6	0.8	5.5
	1643.4	1638.4	8.0	0.0	0.0	0.9
	1638.4	1633.4	8.0	-	-	1.7
	1633.4	1628.4	8.0	0.7	4.4	5.1
	1628.4	1623.4	8.0	5.1	3.1	6.5
	1623.4	1603.0	32.8	4.2	7.3	-
	1603.0	1599.0	6.4	2.0	1.1	-
	1599.0	1596.0	4.8	0.6	9.6	-
	Entire Reach Average			2.0	3.3	4.0

noticeable increasing trend than in the islands. Consequently, the 1998 densities are about double the 1974 values.

In summary, the densities of bars and islands in the Fort Peck Reach have fluctuated during the time period between 1974 and 1998 apparently with a slight increasing trend. This increasing trend is more apparent in the bars than in the islands.

It should also be noted that in the Fort Peck Reach there is generally no notable bank stabilization.

5.1.4. Sediment Gradation Analysis.

Figure 5.4 shows the reach average gradation curves in the Fort Peck Reach for the habitat bars, non-habitat bars, tributaries, arroyos, banks, and channel bed. The D_{10}, D_{50}, and D_{90} values for these features are shown in Table 5.2. The individual geomorphic reach gradation curves for the banks, habitat bars, non-habitat bars, tributaries, and arroyos are shown in Figures 5.5, 5.6, 5.7, 5.8, and 5.9, respectively.

Table 5.3 presents the average bank gradation curves that were developed to represent each geomorphic reach in the Fort Peck Reach. These data are also shown graphically in Figure 5.5. An overall average bank gradation curve for the entire Fort Peck Reach is also provided in Figure 5.5. Because of a change in the bank characteristics within GR 2, two gradation curves were needed to represent this reach, while a single curve was used for GRs 7 and 8. The remaining reaches each had a single gradation curve for the banks. The gradation curves for the habitat bars in the Fort Peck Reach are shown in Figure 5.6. As shown in Figure 5.6, with the exception of one location (WPT 197 - GR 5) there are essentially no fines (less than 0.063 mm) found in the habitat bars. At WPT 197 - GR 5, approximately 50% of the material was finer than 0.063 mm. The exact reason for this is not clear, but it appears to be related to sampling points that were sited in a location with a significant vegetative cover. Regardless of the reason, the results were somewhat atypical of all the other habitat bars that were found in this reach as well as in the other three study reaches, and therefore, the data for WPT 197 were not included in the calculation of the average values for the reach.

Figure 5.4 indicates that the non-habitat bars are generally slightly finer than the habitat bars, but come together at about the 90% level. Likewise, Figure 5.4 reveals that the banks are generally slightly finer than the bars. Examination of the samples taken near the mouths of tributaries and arroyos shows a somewhat wider range, with considerable amounts of fines as well as some coarse material in the 20-mm to 30-mm range.

As indicated in Figure 5.4 there are essentially no fines (less than 0.063 mm) present in the bed. The average bed D_{10} value for the entire reach is about 0.21 mm (Table 5.2) As indicated in Table 5.2, the average D_{10} for the habitat bars is about 0.16 mm. This value corresponds to about the D_5 for the bed. This suggests for the Fort Peck Reach that material finer than about 0.16 mm is not in appreciable quantities in the bed and habitat bars. Therefore, sediment load composed of material greater than 0.16 mm may be considered bed material load while material finer than this behaves as wash load.

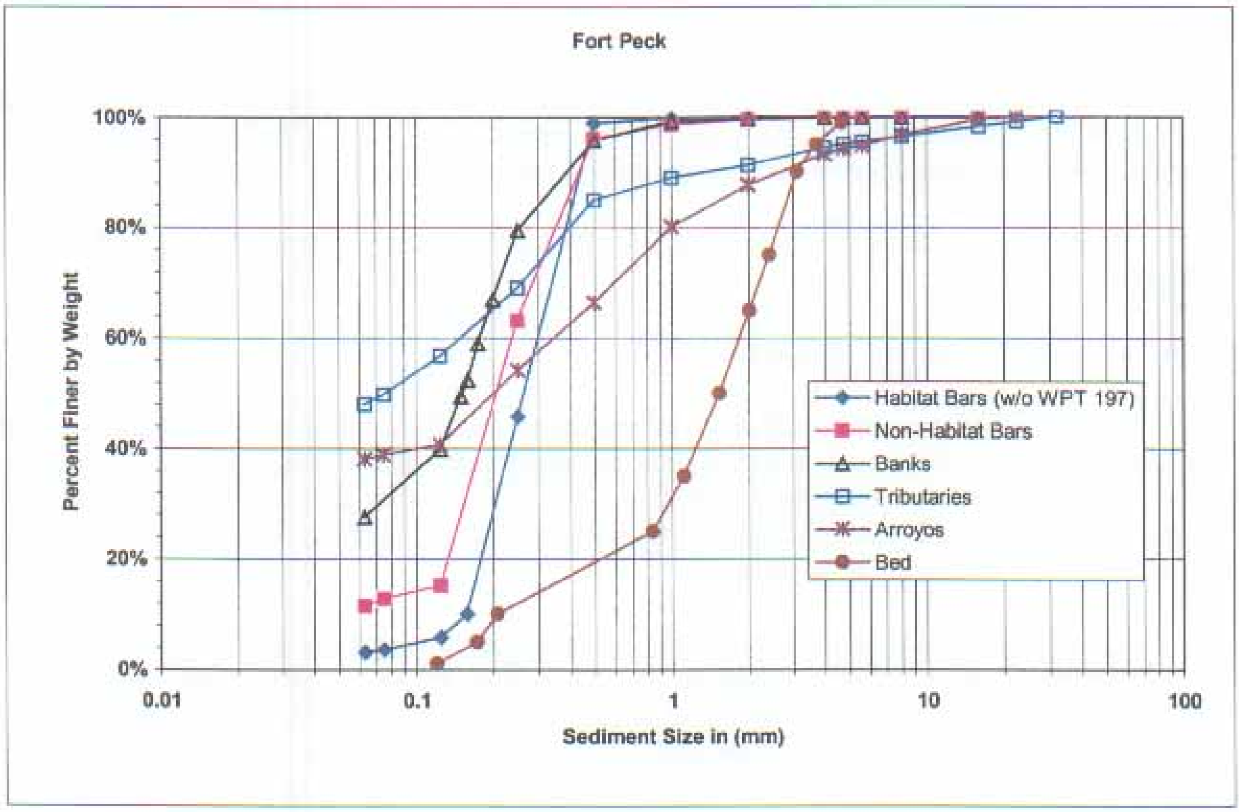


Figure 5.4. Reach average gradation curves for the habitat bars, non-habitat bars, tributaries, arroyos, banks, and channel bed for the Fort Peck Reach.

Table 5.2 Fort Peck Reach average D_{10}, D_{50} and D_{90} values for habitat bars, non-habitat bars, tributaries, arroyos, banks, and channel bed.

Percent	Reach Average Habitat Bar (mm)	Reach Average Non-habitat Bar (mm)	Reach Average Tributary (mm)	Reach Average Arroyo (mm)	Reach Average Banks (mm)	Reach Average Bed (mm)
D_{10}	0.16	-	-	-	-	0.21
D_{50}	0.26	0.21	0.08	0.20	0.15	1.5
D_{90}	0.44	0.44	1.41	2.7	0.40	3.1

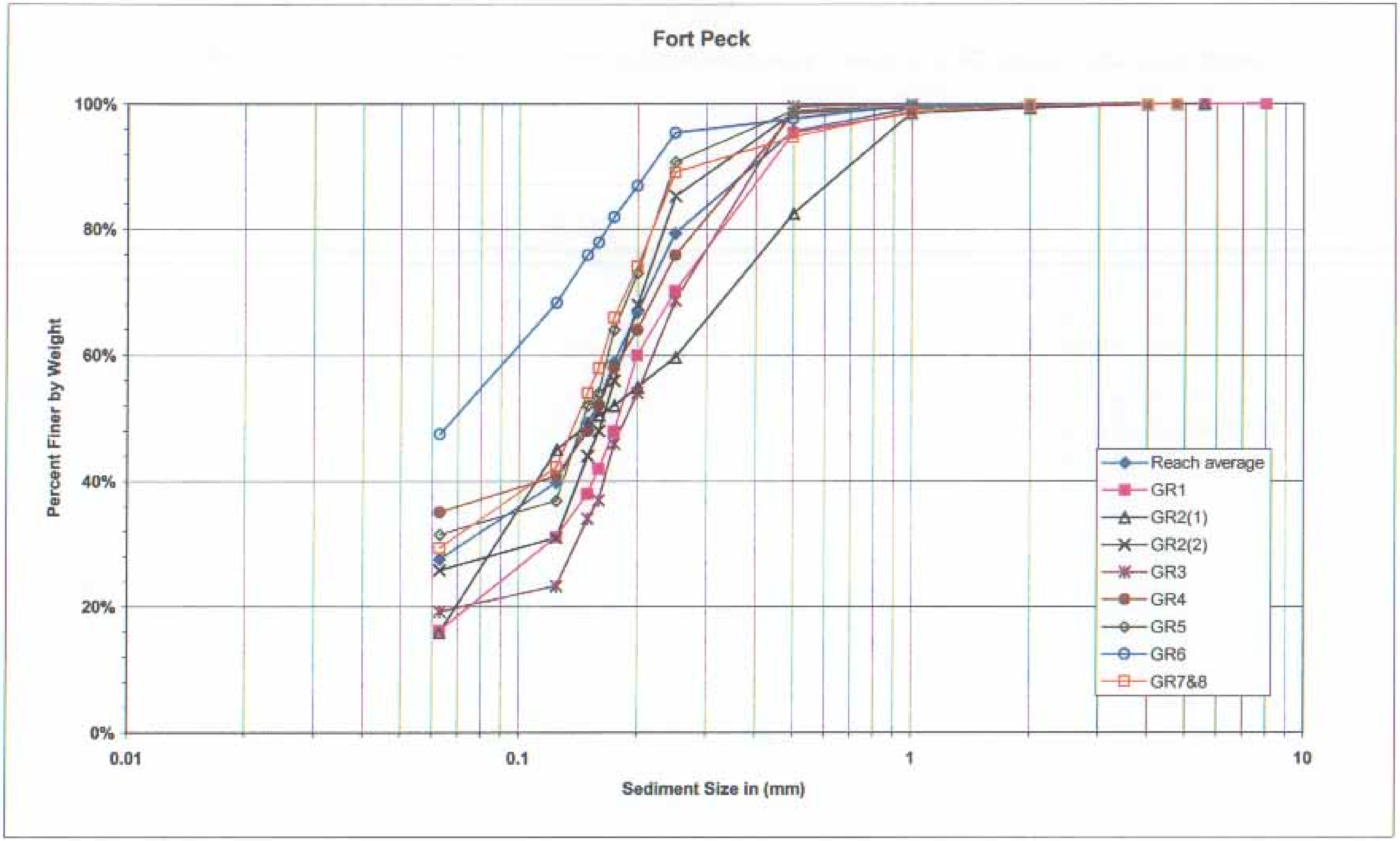


Figure 5.5 Average bank gradation curves for individual geomorphic reaches and the reach average for the Fort Peck Reach.

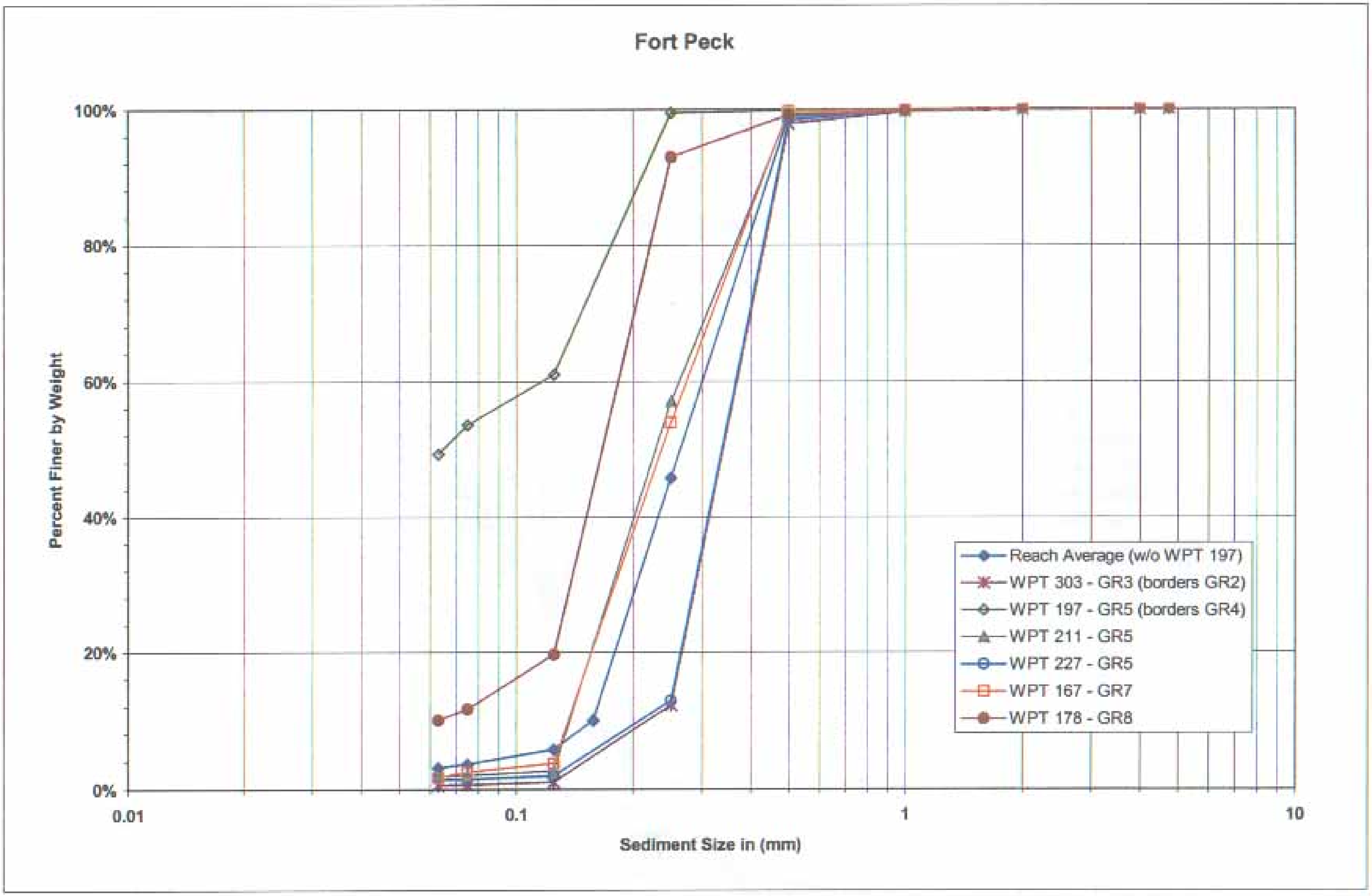


Figure 5.6 Gradation curves for each habitat bar and the reach average for the Fort Peck Reach.

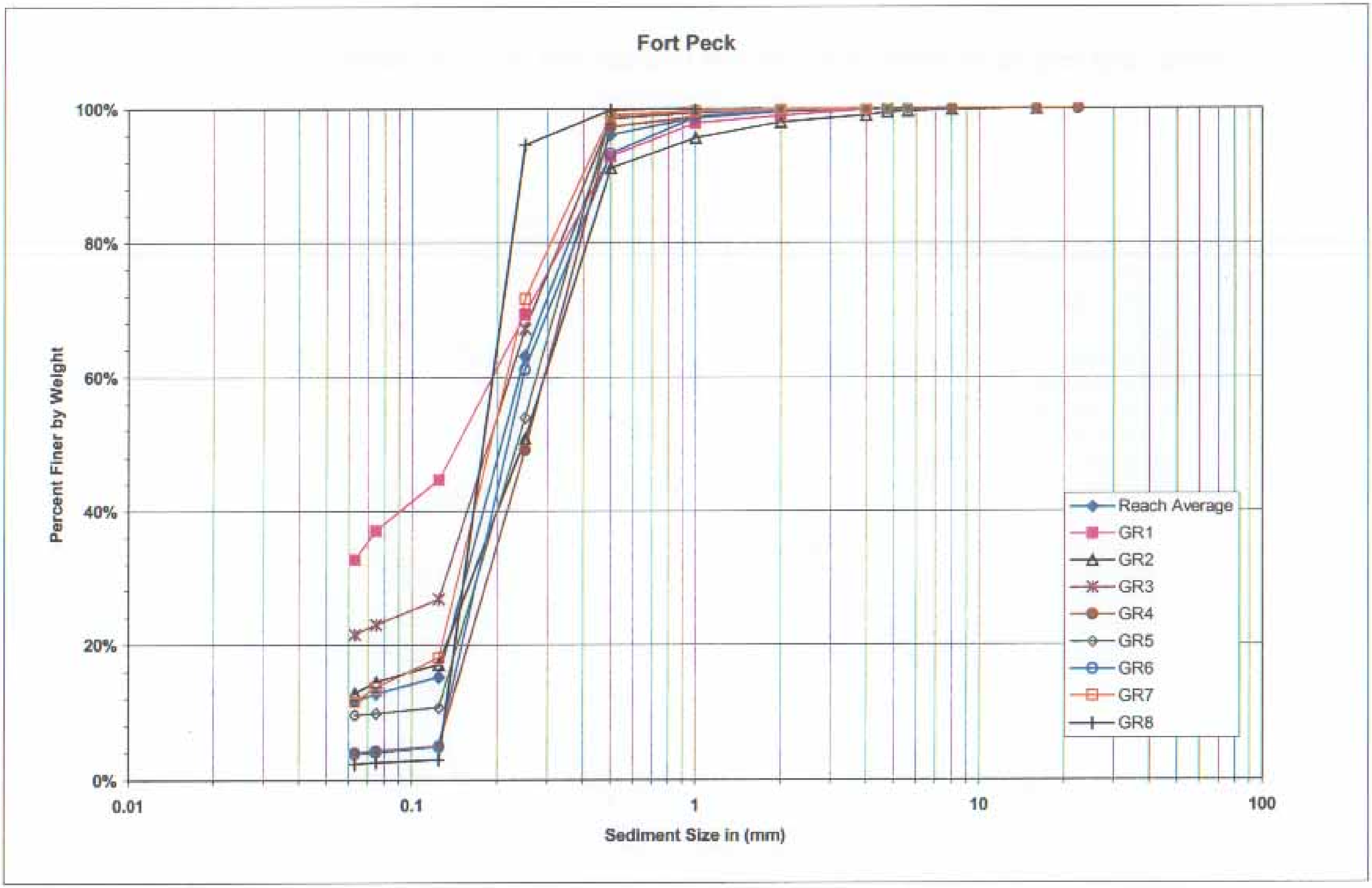


Figure 5.7 **Average non-habitat bar gradation curves for individual geomorphic reaches and the reach average for the Fort Peck Reach.**

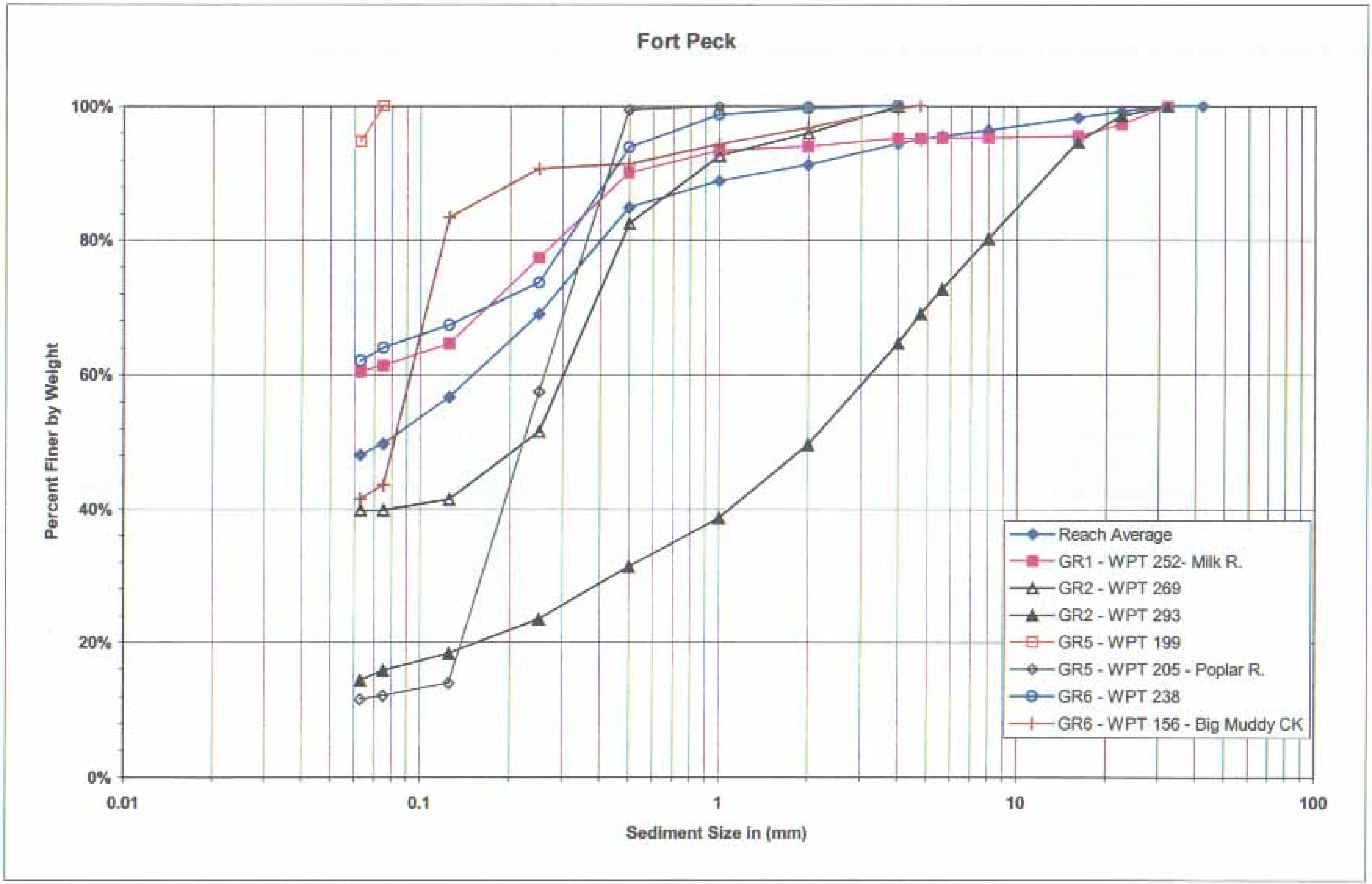


Figure 5.8 Gradation curves for each tributary and the reach average for the Fort Peck Reach.

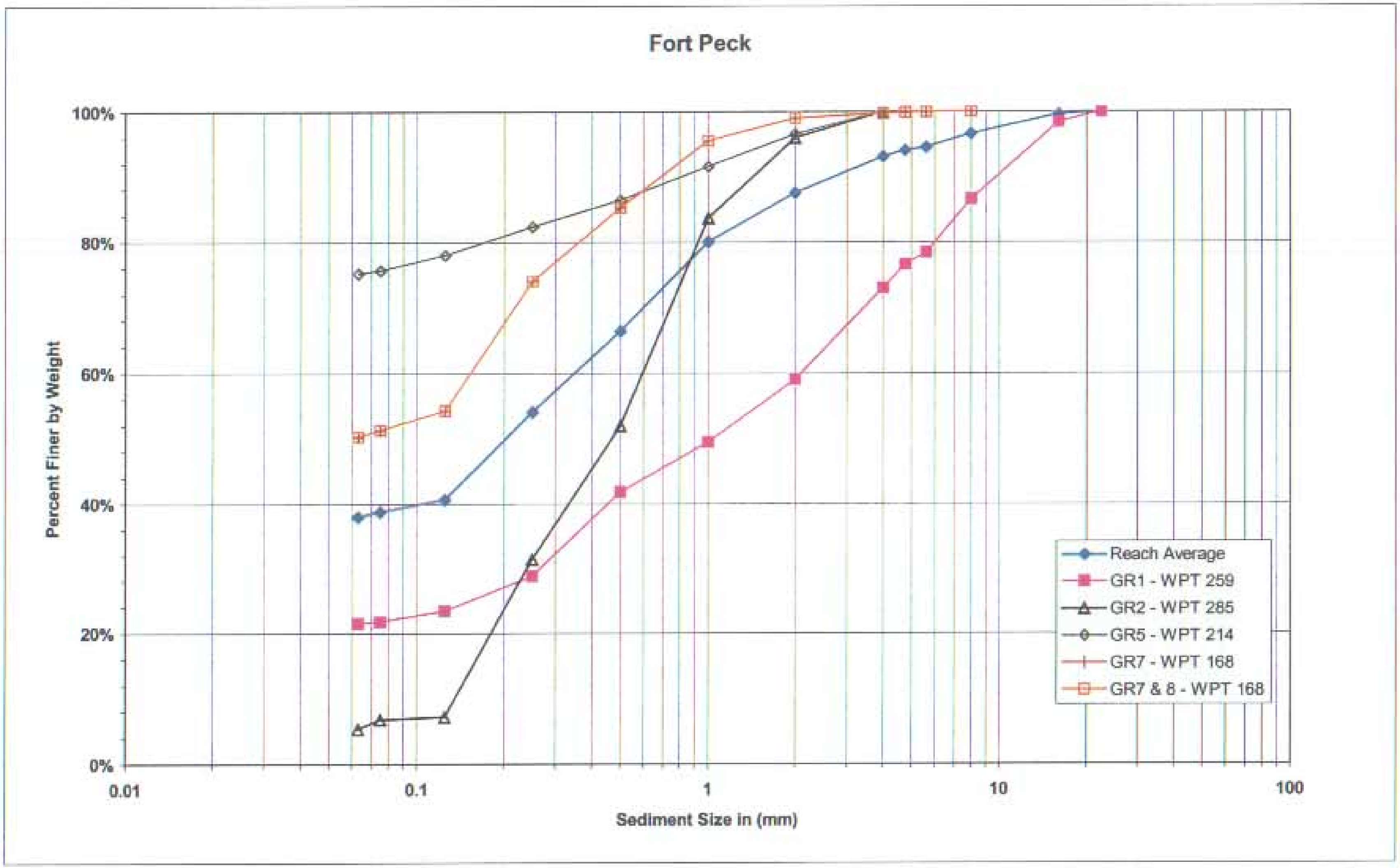


Figure 5.9 Gradation curves for each arroyo and the reach average for the Fort Peck Reach.

Table 5.3 Average bank gradation curves for each geomorphic reach in the Fort Peck Reach.

Geomorphic Reach (RM)	WPT	Grain Size (mm) Percent Finer by Weight															
		0.063	0.125	0.14	0.15	0.16	0.175	0.2	0.25	0.5	1	2	4	4.75	5.6	8	16
GR 1 (1766-1750)	247,249,250,251, 254,256,257,262, 264	16.09%	31.07%	34.00%	38.00%	42.00%	48.00%	60.00%	70.18%	95.36%	98.49%	99.48%	99.83%	99.91%	99.95%	99.99%	100%
GR 2 Part I (1749-1727)	267,268,270,271, 272,273,274,275, 277,279,281,282, 283,284,285,286, 287,290,291	15.92%	45.05%	47.00%	49.00%	50.50%	52.00%	55.00%	59.67%	82.52%	98.55%	99.37%	99.93%	99.98%	99.99%	99.99%	100%
GR 2 Part II (1726-1713)	294,295,296,297, 298,299,300,301 302	25.80%	31.00%	36.00%	44.00%	48.00%	56.00%	68.00%	85.30%	98.58%	99.43%	99.95%	99.97%	99.98%	99.99%	99.99%	100%
GR 3 (1712-1700)	305,306,307,310, 311	19.13%	23.29%	28.00%	34.00%	37.00%	46.00%	54.00%	68.63%	99.61%	99.95%	99.99%	99.99%	99.99%	99.99%	99.99%	100%
GR 4 (1699-1686)	183,184,185,186, 190,192,193,194, 195,196	35.04%	40.80%	44.00%	48.00%	52.00%	58.00%	64.00%	75.89%	98.47%	99.39%	99.91%	99.99%	99.99%	99.99%	99.99%	100%
GR 5 (1685-1654)	198,202,204,208, 209,212,213,215, 216,217,218,219, 222,224,226	31.55%	36.88%	42.00%	52.00%	54.00%	64.00%	73.00%	90.75%	98.93%	99.68%	99.98%	99.99%	99.99%	99.99%	99.99%	100%
GR 6 (1653-1621)	234,235,237,239, 240	47.58%	68.42%	72.00%	76.00%	78.00%	82.00%	87.00%	95.48%	97.64%	99.88%	99.98%	99.99%	99.99%	99.99%	99.99%	100%
GRs 7 & 8 (1620-1582)	159,160,161,162, 164,166,169,170, 171,172,176,177	29.30%	42.28%	46.00%	54.00%	58.00%	66.00%	74.00%	89.07%	94.71%	98.73%	99.76%	99.93%	99.99%	99.99%	99.99%	100%

As shown in Table 5.3, the percent of the bank material finer than 0.063 mm ranged from about 16% to 48% with an average of about 27%. Thus, about 27% of the materials eroded from the banks are fines (silts and clays), which are essentially nonexistent in the bed and habitat bars. The percent of the bank material finer than 0.16 mm (corresponding to the lower cutoff of the bed and habitat bar material size in this reach) ranged from about 37% to 78% with an average of about 52%. Thus, for the Fort Peck Reach, about 48% of the material eroded from the banks is of the same size as the material found in appreciable quantities in the bed or habitat bars, and thus contributes to the bed material load.

5.1.5. Bank Erosion Analysis.

A summary of the bank erosion results for the Fort Peck Reach is shown in Table 5.4. As indicated in Table 5.4, GRs 5 through 8 have the largest annual erosion rates per kilometer in the Fort Peck Reach. Conversely, GR 1 has the smallest annual erosion rate per kilometer. Because the downstream extent of the 1998 GIS available orthophotos was about RM 1625, there was no bank erosion data calculated for GRs 7 and 8. The results shown in Table 5.4 for these two reaches were taken directly from Pokrefke *et al.* (1998).

Table 5.4 Fort Peck bank erosion from 1983 to 1998.

Geomorphic Reach (RM)	Left Bank Erosion (m^3)	Right Bank Erosion (m^3)	Total Volume (m^3)	Annual Volume (m^3/yr)	Distance River (km)	Annual Volume/km (m^3/yr/km)
GR 1 (1768-1750)	184,683	172,769	357,452	23,846	29.0	823
GR 2 (1749-1713)	1,225,656	1,978,594	3,204,250	213,617	57.9	3,688
GR 3 (1712-1700)	416,120	1,125,788	1,541,908	102,794	19.3	5,324
GR 4 (1699-1686)	662,032	804,044	1,466,075	97,738	20.9	4,673
GR 5 (1685-1654)	1,982,575	3,954,942	5,937,517	395,834	49.9	7,936
GR 6 (1653-1621)	3,296,358	3,644,329	6,940,687	462,712	51.5	8,987
GRs 7& 8 (1620-1599)	2,136,670	986,040	3,122,710	312,271	35.2	8,862
Total	9,904,093	12,666,505	22,570,599	1,608,797	263.7	6,101

Note: Total in column 7 is the total annual volume ÷ total river distance

5.1.6. Sediment Budget.

As discussed in Section 5.1.4, the bed material load in the Fort Peck Reach is comprised of material greater than about 0.16 mm. Therefore, the bank erosion volumes used in the Fort Peck sediment budget reflect the contribution of bank material greater than 0.16 mm. The sediment budget for the Fort Peck Reach is shown in Table 5.5. Once again it should be noted that the results for GRs 7 and 8 were derived entirely from the Pokrefke *et al.* (1998) data and do not reflect the bank line comparisons between 1983 and 1998. As shown in Table 5.5, there is a general increase in bed material transport with distance downstream as far as about GR 4. Downstream of this, the transport remains relatively constant and actually decreases in GRs 7 and 8. Thus, the upstream segment of the Fort Peck Reach down to about GR 4 (RM 1686 to RM 1699) reflects a net erosional tendency while downstream of this, the channel approaches dynamic equilibrium and then becomes aggradational. These trends are generally comparable to the trends discussed in Section 5.1.1, which showed the upstream portion of the river above about RM 1679 to RM 1700 to be degradational while the downstream reaches were aggradational.

Table 5.5 Fort Peck sediment budget with >0.160 mm bed material size.

Geomorphic Reaches (RM)	Erosion		Deposition		Net Sediment Transport from Erosion & Deposition (m^3/yr)	Upstream Sediment Supply (m^3/yr)	Sediment Transport Budget (m^3/yr)
	Bank (1983-1998) (m^3/yr)	Bed (1968-1978) (m^3/yr)	Bank (1968-1978) (m^3/yr)	Bed (1968-1978) (m^3/yr)			
GR 1 (1768-1750)	-13,831	-142,964	21,761	42,929	-92,104		-92,104
GR 2 (1749-1713)	-108,329	-238,976	93,122	30,438	-223,745	-92,104	-315,849
GR 3 (1712-1700)	-64,803	-34,104	1,209	24,255	-73,442	-315,849	-389,292
GR 4 (1699-1686)	-46,945	-251,561	42,889		-255,617	-389,292	-644,909
GR 5 (1685-1654)	-182,203	-170,633	100,791	54,650	-197,394	-644,909	-842,303
GR 6 (1653-1621)	-101,863	-97,388	184,369		-14,883	-842,303	-857,186
GRs 7 & 8 (1620-1599)	-131,167	-50,447	65,815	240,488	124,690	-857,186	-732,496
Total (1768-1599)	-649,140	-986,073	509,956	392,761	-732,496		

As a check, the bed material calculations performed herein were compared with the measured suspended sediment loads at Culbertson, Montana. The average annual measured suspended load at Culbertson for the period 1971-1999 is about 1,700,000 m^3/yr. The average coarse fraction (greater than 0.062 mm) of the measured suspended load data is about 40%. Therefore, the average annual sand load is about 680,000 m^3/yr. The annual bed material load calculated in GR 6 was about 856,000 m^3/yr. A direct comparison of these two values is not possible for two reasons: (1) the calculated sediment budget values reflect the bed material load (greater than 0.16 mm) and therefore should be somewhat less than the sand load which includes all sand sizes (greater than 0.062 mm); and (2) since the measured sand load does not include the unmeasured portion of the load, it should be less than the total bed material load calculated by the sediment budget. However, if it is assumed that these two factors tend to offset each other, then the two methods should produce values within about the same range. Based on this assumption it appears that the calculated bed material loads appear to be an acceptable range when compared to the measured suspended sand load data.

Table 5.6 shows the reduction in the supply of bed material (greater than 0.16 mm) from bank erosion that would result from stabilization of 10% to 100% of the eroding areas for each of the GRs. As illustrated in Table 5.6, the impacts of bank stabilization vary from reach to reach. For instance, in GR 2, the material supplied from the banks was about 34% of the total bed material load in that reach. Therefore, if all bank erosion was eliminated by bank stabilization, there would be a reduction in the supply of bed material sized sediment in this reach of about 34%. As a consequence, the river would acquire this additional load from scouring the bed, bars, and/or remaining unprotected banks in the reach. In the other reaches, the bank contributions range from about 7% to 21%. Therefore, the impacts on the bed material load associated with bank stabilization in these reaches should be less. Table 5.6 also allows for the determination of the impacts associated with only stabilizing some of the eroding areas. For instance, in GR 2, if 30% of the eroding areas were stabilized, there would be about a 10% reduction in the supply of bed material sized sediment to the reach. However, if 60% of the eroding areas were stabilized, the reduction would be almost 20%.

Table 5.6 also shows the reach average values for the entire Fort Peck Reach. Considering the entire Fort Peck Reach, the banks supply about 17% of the bed material load. Thus, on a gross reach level, the effects of stabilizing all eroding areas would reduce the supply of bed material by about 17%.

5.1.7. Discussion of Results.

When the banks in the Fort Peck Reach are compared to the bars, it is found that the bars are generally somewhat coarser than the banks. Habitat bars were also found to be somewhat coarser than the non-habitat bars. In fact the habitat bars in this reach are composed almost entirely of sand sized material with the average D_{10} being about 0.16 mm. The channel bed is slightly coarser than the habitat bars with an average D_{10} of about 0.21 mm. A grain size of 0.16 mm was selected to represent the lower size limit of material found in appreciable quantities in the bed and habitat bars for this reach. The percent of bank material coarser than 0.16 mm ranged from about 22% to 63% with an average of about 48%. This suggests that for the Fort Peck Reach, about 48% of the material eroded from the banks is of a size found in appreciable quantities in the bed or habitat bars.

The sediment budget for the Fort Peck Reach suggests that the upper portion of the reach extending downstream to the vicinity of RM 1686 to RM 1699, exhibits degradational tendencies while the downstream portion of the reach appears to be in dynamic equilibrium or slightly aggradational. The total annual volume of material eroded from the channel banks in the Fort Peck Reach is about 1,609,000 m^3/yr, or about 6,000 $m^3/yr/km$. While this is a large number, it must be remembered that just less than half of this material contributes to the bed material load in the reach. Therefore, the overall contribution from bank erosion to the bed material load in the Fort Peck Reach is only about 17%. At the reach scale, GRs 2 and 5 had the largest bank contributions at about 34% and 22%, respectively. The reach with the lowest bank contributions was GR 4 at about 7%.

Table 5.6 Bank stabilization impact on the Fort Peck Reach.

Fort Peck budget with >0.16 mm bed material size.

Revetment Percentage	Geomorphic Reaches							
	Reduction of Bank Contribution GR 1 RM 1768- RM 1750	Reduction of Bank Contribution GR 2 RM 1749- RM 1713	Reduction of Bank Contribution GR 3 RM 1712- RM 1700	Reduction of Bank Contribution GR 4 RM 1699- RM 1686	Reduction of Bank Contribution GR 5 RM 1685- RM 1654	Reduction of Bank Contribution GR 6 RM 1653- RM 1621	Reduction of Bank Contribution GRs 7& 8 RM 1620- RM 1599	Reach Average Reduction of Bank Contribution RM 1768 – RM 1599
10	2%	3%	2%	1%	2%	1%	2%	2%
20	3%	7%	3%	1%	4%	2%	4%	3%
30	5%	10%	5%	2%	6%	4%	5%	5%
40	6%	14%	7%	3%	9%	5%	7%	7%
50	8%	17%	8%	4%	11%	6%	9%	8%
60	9%	21%	10%	4%	13%	7%	11%	10%
70	11%	24%	12%	5%	15%	8%	13%	12%
80	12%	27%	13%	6%	17%	10%	14%	13%
90	14%	31%	15%	7%	19%	11%	16%	15%
100	15%	34%	17%	7%	22%	12%	18%	17%

The supply of suitably sized sediment from the banks is just one factor that may influence bar morphology. Another factor that is very important is the local geometry of the reach. This analysis revealed a strong relationship between channel width and the presence or absence of bar formation. Reaches with bars and islands present were much wider than reaches without bars. The mean channel width for reaches where no bars were present was about 227 m, while in the reaches with bars and islands the mean width was about 327 m and 461 m, respectively. Seventy five percent of the reaches with no bars present had a channel width less than 255 m, while only 17% of reaches with bars, and 2% of reaches with islands had channel widths less than 255 m. Thus, for the Fort Peck Reach a channel width in the range of about 255 m appears to be a threshold zone below which it is very unlikely that bars will exist. Therefore, channel width appears to be one of the dominant factors with respect to bar and island formation. Recognition of the relationship between channel width and bar morphology is important for the effective management of this system to minimize impacts to channel bars.

It should be remembered that as with any sediment transport analysis, there is considerable uncertainty in these results. Consequently, the results presented herein do not represent absolute values, but rather, should be viewed as providing a reasonable approximation of the general trends in the reach.

5.2. Garrison Reach

5.2.1. General Characteristics of the Garrison Reach.

The Garrison study reach extends from RM 1390 just downstream of the Garrison Dam, to RM 1311 (Figure 5.10). This reach is regulated by the Garrison Dam, which was completed by the USACE in 1953. The mean annual flow at the Bismarck gauge is about 655 CMS. Bed material in the reach is predominately sand with occasional outcrops of gravel. The channel in this reach is relatively straight with sinuosity ranging from about 1.0 to 1.25. Many reaches exhibit a moderate to high degree of braiding with numerous bars and islands. The channel width ranged from about 130 m to 1,350 m, with an average width of about 615 m. The energy slope for the Garrison Reach, calculated from the HEC-RAS analysis, ranges from about 0.0001 to 0.00013. The most important tributaries in this reach are the Heart and Knife Rivers, but taken together, their contribution to the total flow in this reach is only about two percent. Bank heights in this reach generally range from about 3 to 13 m with an average bank height of about 5.2 m. For this study, the Garrison Reach was divided into six GRs.

The specific gauge records for the Garrison Reach are shown in Appendix C of the data supplement CD ROM. The Garrison Reach has several gauges with recent data. These include the gauges at Stanton, Fort Clark, Hensler, Washburn, Price, and Bismarck. Very limited data were available on the tributaries. The specific gauge records generally reveal a degradational trend following dam construction. However, this degradational trend began to diminish somewhat in the mid 1970s to early 1980s. Since about the mid 1980s, the gauge records suggest that the river may be approaching a state of dynamic equilibrium.

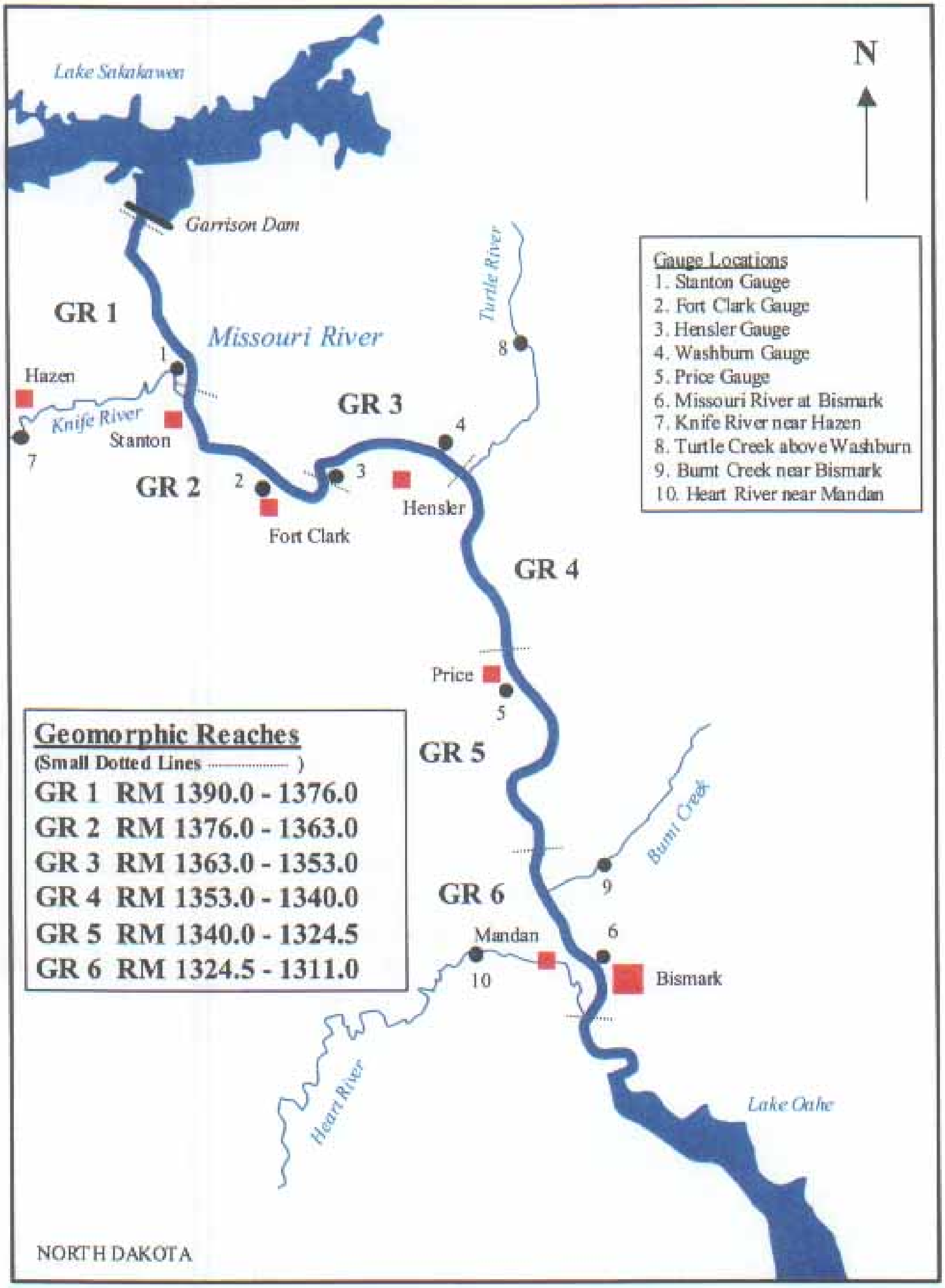


Figure 5.10 Vicinity map for the Garrsion Reach.

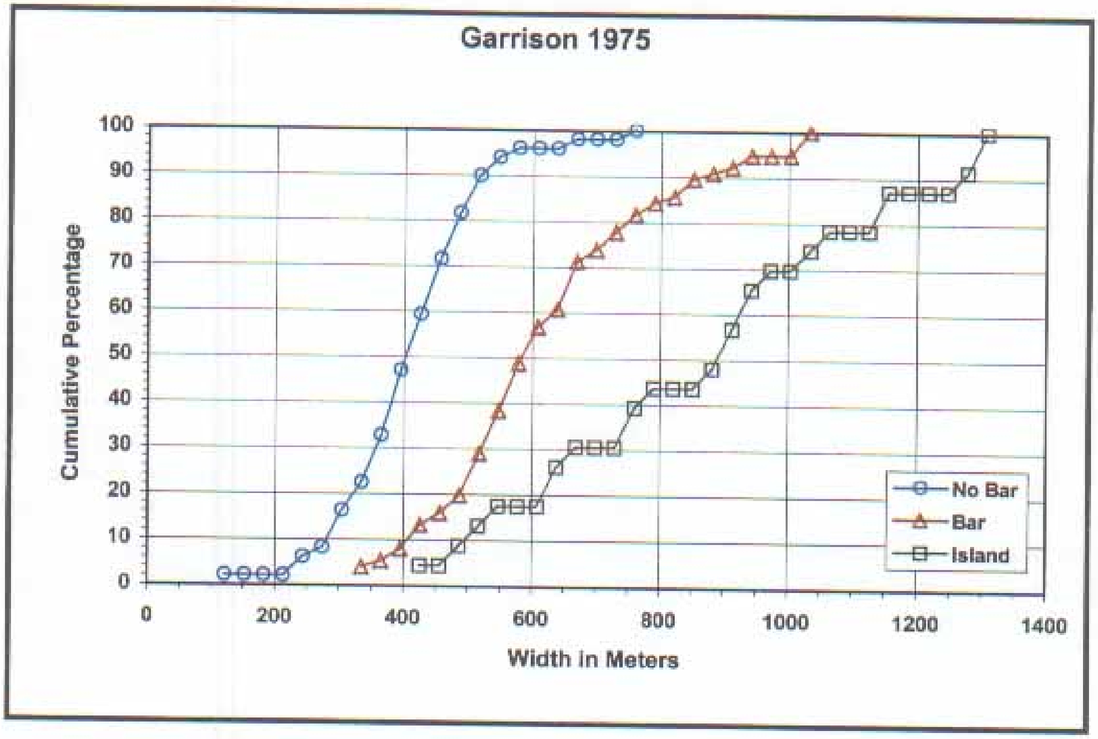
5.2.2. Relationship Between Channel Width and Bars and Islands.

The cumulative distribution relating channel width and the occurrence of bars and islands for two time periods, 1975 and 1997, is shown in Figure 5.11. Box and whisker plots for the data are shown in Figures 5.12. Although there were some minor differences, the general shape of the curves are similar for the two time periods (Figure 5.11). In general, it appears that the width for the 'no bars' and 'bars' reaches are slightly wider in 1997 than in 1975. Figure 5.11 illustrates that reaches with no bars present are much narrower than reaches with bars or islands present. The plots in Figures 5.11 and 5.12 reveal that in 1997 the mean value of channel width for reaches with no bars was about 534 m, while the reaches with bars, and those with islands had mean channels widths of 693 m and 860 m, respectively. Likewise, 75% of the reaches with no bars had channel widths less than about 630 m, while only about 35% of the reaches with bars had a channel width less than 630 m. Only about 17% of the reaches with islands had channel width less than 630 m. Thus, for the Garrison Reach a channel width in the range of about 630 m appears to be a threshold zone below which it is very unlikely that bars will exist. These data suggest a strong relationship between channel width and the presence of bars and islands. Thus, ensuring sufficient channel width may be a critical factor in the formation of bars and islands in the Garrison Reach.

5.2.3. Bar and Island Density Analysis.

The results of the bar and island density analysis for the Garrison Reach are shown in Table 5.7. As shown in Table 4.16 the dates of the aerial photography and the associated discharges were October 10,1976 (379 CMS), October 25, 1990 (292 CMS), and August 5, 1997 (1,415 CMS). Since the discharge on the day of the photography in 1997 was 4 to 5 time greater than in the previous two periods, it might be expected that the bar and island density numbers would be somewhat less. As shown in Table 5.2.1, most of the reaches experienced a decrease in island density between 1976 and 1997. However, because of the disparity in discharges between these two time periods, it is difficult to establish whether these changes are real or a consequence of the increased flow. Comparing the 1976 and 1990 data, it is seen that all but one of the reaches experienced an increase in island density. As shown in Table 5.7, the bar density has fluctuated with some reaches experiencing decreases and other increases, with the overall reach average remaining approximately unchanged.

Also shown in Table 5.7, is the percent of bank line that is stabilized for each reach. Stabilization percentages range from about 9% to 36%. Since the stabilization works were constructed after 1976, an attempt was made to determine if there was a relationship between the percent stabilization and the increases or decreases in bar and island density. However, examination of Table 5.7 does not reveal any obvious trends between stabilization percentage and bar or island density changes.



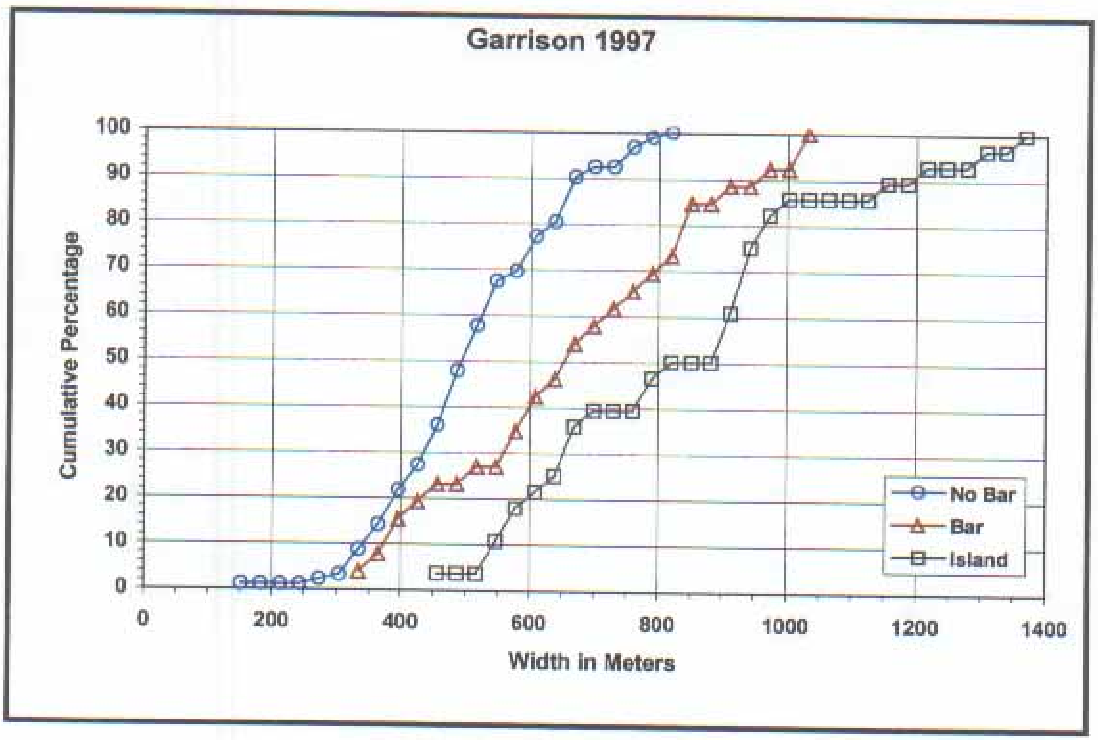
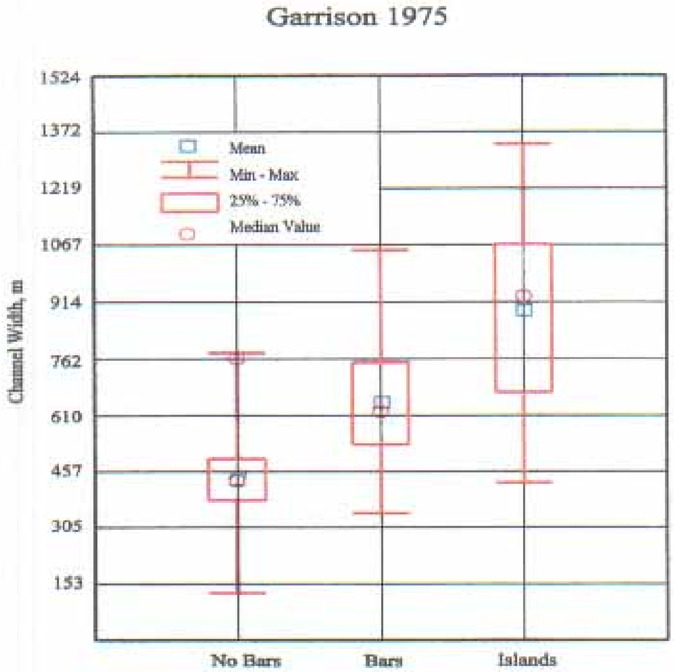


Figure 5.11 Cumulative distribution of channel width and occurrence of bars and islands for 1975 and 1997, for the Garrison Reach.



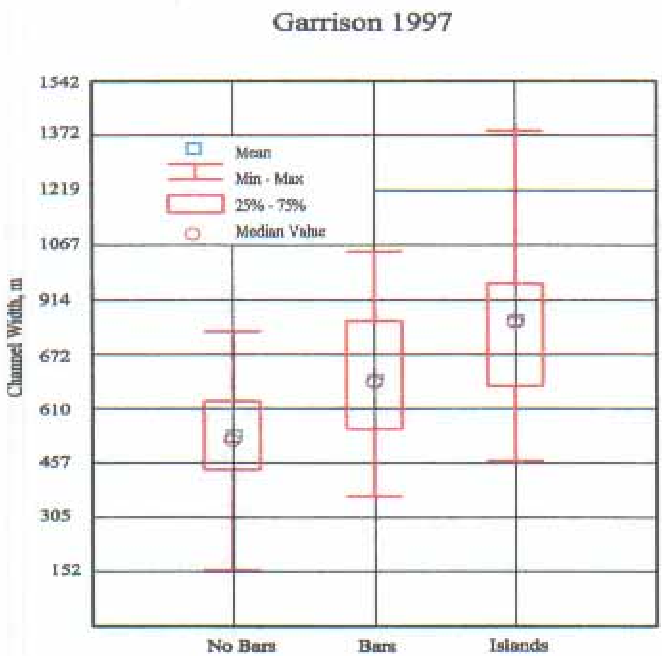


Figure 5.12 Box and whisker plots displaying the cumulative distribution of channel width and occurrence of bars and islands for 1975 and 1997, for the Garrison Reach.

Table 5.7 Island and sandbar density and percent of bank line stabilized for Garrison Reach.

	Garrison Reach, Island and Sandbar Density						Aerial Mosaic June 3, 1981		
	1960 RM		Reach Length (km)	Density (ha/km)			Percent of Reach Revetted		
	Upstream	Downstream		As of 1976	As of 1990	As of 1997	Left	Right	Total
Islands	1390	1370	32.2	12.0	17.2	15.3	5.0	12.8	8.9
	1370	1365	8.0	38.1	14.7	0.0	72.3	0.0	36.2
	1365	1355	16.1	0.0	22.4	0.0	30.3	19.3	24.8
	1355	1345	16.1	25.1	29.4	5.6	22.7	19.3	21.0
	1345	1340	8.0	6.6	10.1	3.0	11.7	43.6	27.7
	1340	1325	24.1	10.8	20.5	3.8	20.7	28.4	24.6
	1325	1315	16.1	33.4	33.8	38.0	39.4	24.1	31.7
	Entire Reach Average		120.7	16.9	21.0	10.9	-	-	-
Sandbars	1390	1370	32.2	23.1	14.9	7.8	5.0	12.8	8.9
	1370	1365	8.0	70.4	41.7	45.3	72.3	0.0	36.2
	1365	1355	16.1	33.8	36.8	29.8	30.3	19.3	24.8
	1355	1345	16.1	26.4	23.5	33.4	22.7	19.3	21.0
	1345	1340	8.0	12.2	33.4	18.6	11.7	43.6	27.7
	1340	1325	24.1	17.2	29.8	34.9	20.7	28.4	24.6
	1325	1315	16.1	15.6	13.9	21.4	39.4	24.1	31.7
	Entire Reach Average		120.7	26.4	25.9	24.6	-	-	-

5.2.4. Sediment Gradation Analysis.

Figure 5.13 shows the reach average gradation curves in the Garrison Reach for the habitat bars, non-habitat bars, tributaries, arroyos, banks, and channel bed. The D_{10}, D_{50}, and D_{90} values for these features are shown in Table 5.8. The individual gradation curves for the banks, habitat bars, non-habitat bars, tributaries, and arroyos are shown in Figures 5.14, 5.15, 5.16, 5.17, and 5.18, respectively.

Table 5.9 presents the average bank gradation curves that were developed to represent each geomorphic reach in the Garrison Reach. These data are also shown graphically in Figure 5.14. An overall average bank gradation curve for the entire Garrison Reach is also provided in Figure 5.14. As indicated in Table 5.9, a single curve was used for GRs 4, 5, and 6. The remaining reaches each had a single gradation curve for the banks. The gradation curves for the habitat bars in the Garrison Reach are shown in Figure 5.15. As shown in Figure 5.15, with the exception of one location (WPT 85 - GR 4) there are essentially no fines (less than 0.063 mm) found in the habitat bars. At WPT 85 - GR 4, approximately 40% of the material was finer than 0.063 mm. This was felt to be somewhat atypical of the other habitat bars that were found in this reach as well as in the other three study reaches, and therefore, the data for WPT 85-GR 4 were not included in the calculation of the average values for the reach.

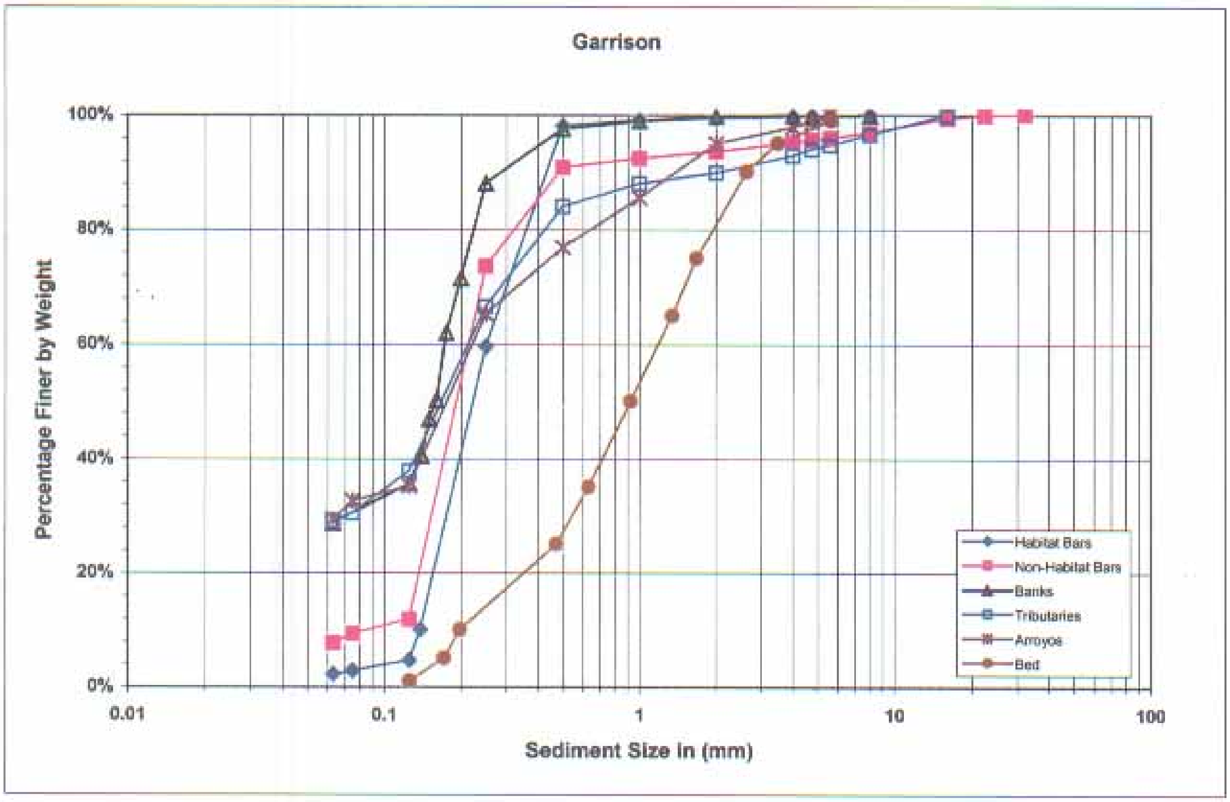


Figure 5.13 Reach average gradation curves for the habitat bars, non-habitat bars, tributaries, arroyos, banks, and channel bed for the Garrison Reach.

Table 5.8 Garrison Reach average D_{10}, D_{50} and D_{90} values for habitat bars, non-habitat bars, tributaries, arroyos, banks, and channel bed.

Percent	Reach Average Habitat Bar (mm)	Reach Average Non-habitat Bar (mm)	Reach Average Tributary (mm)	Reach Average Arroyo (mm)	Reach Average Banks (mm)	Reach Average Bed (mm)
D_{10}	0.14	0.09	-	-	-	0.20
D_{50}	0.22	0.19	0.17	0.18	0.16	0.92
D_{90}	0.43	0.48	2.1	1.4	0.29	2.6

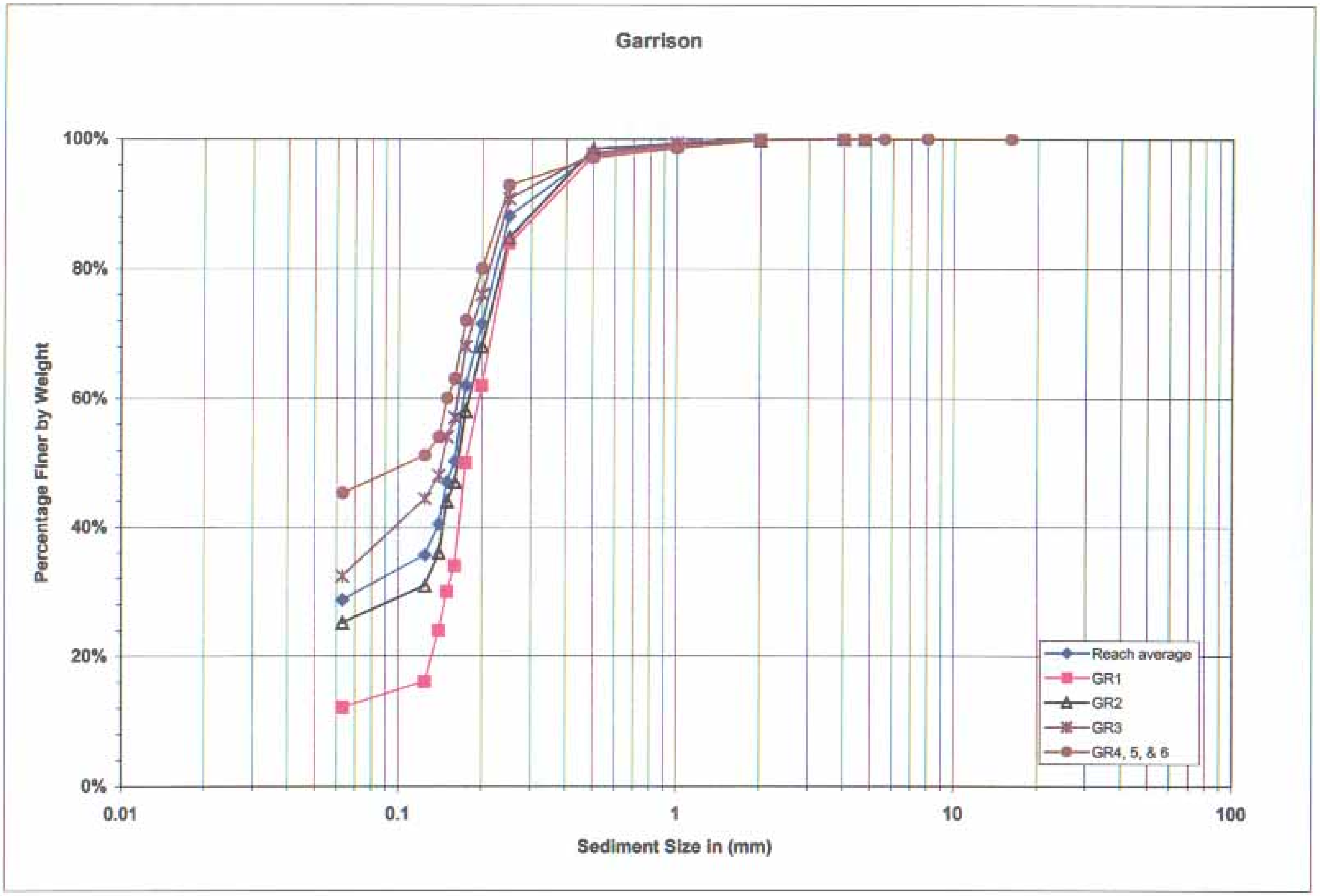


Figure 5.14 Average bank gradation curves for individual geomorphic reaches and the reach average for the Garrison Reach.

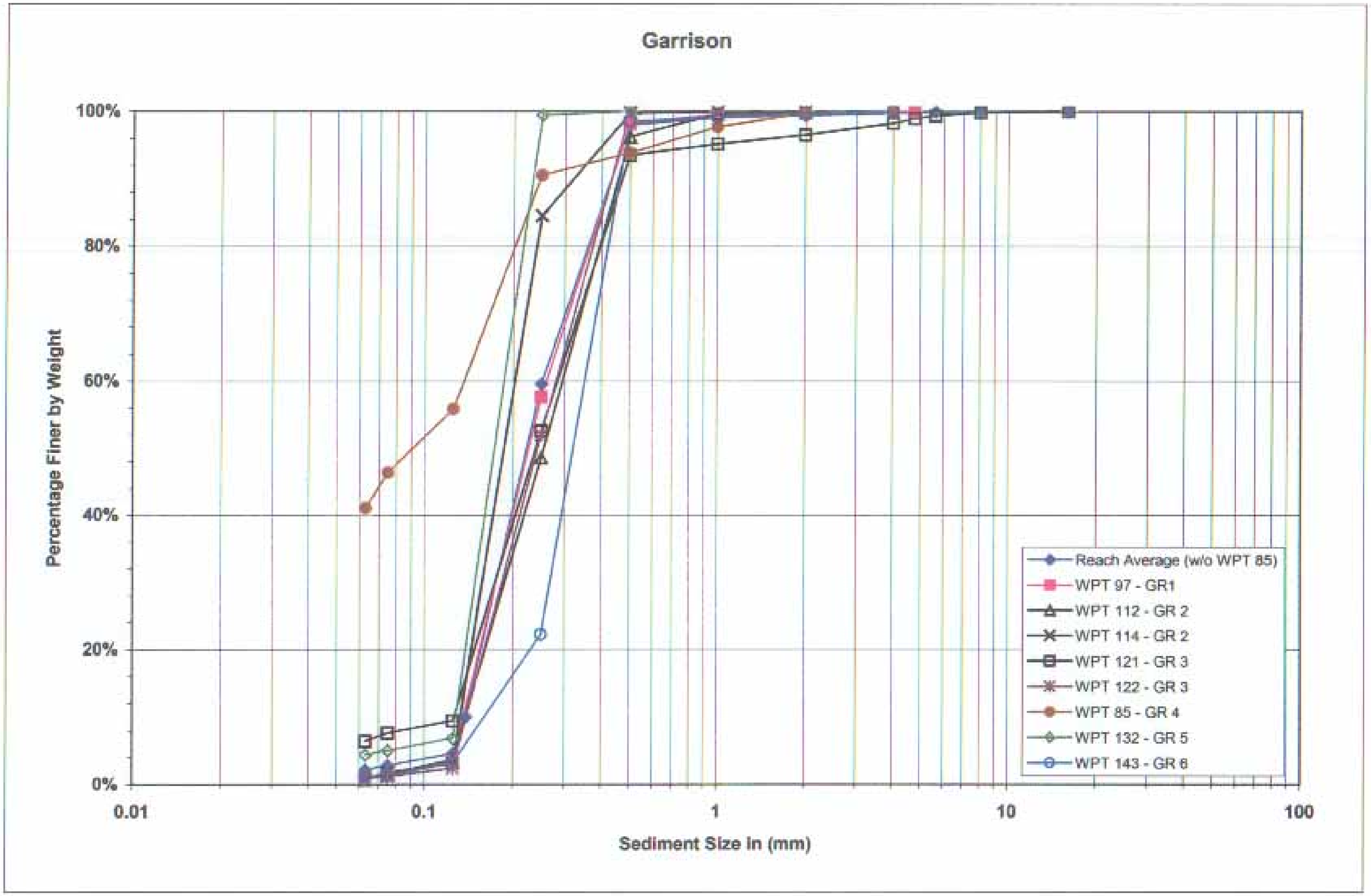


Figure 5.15 Gradation curves for each habitat bar and the reach average for the Garrison Reach.

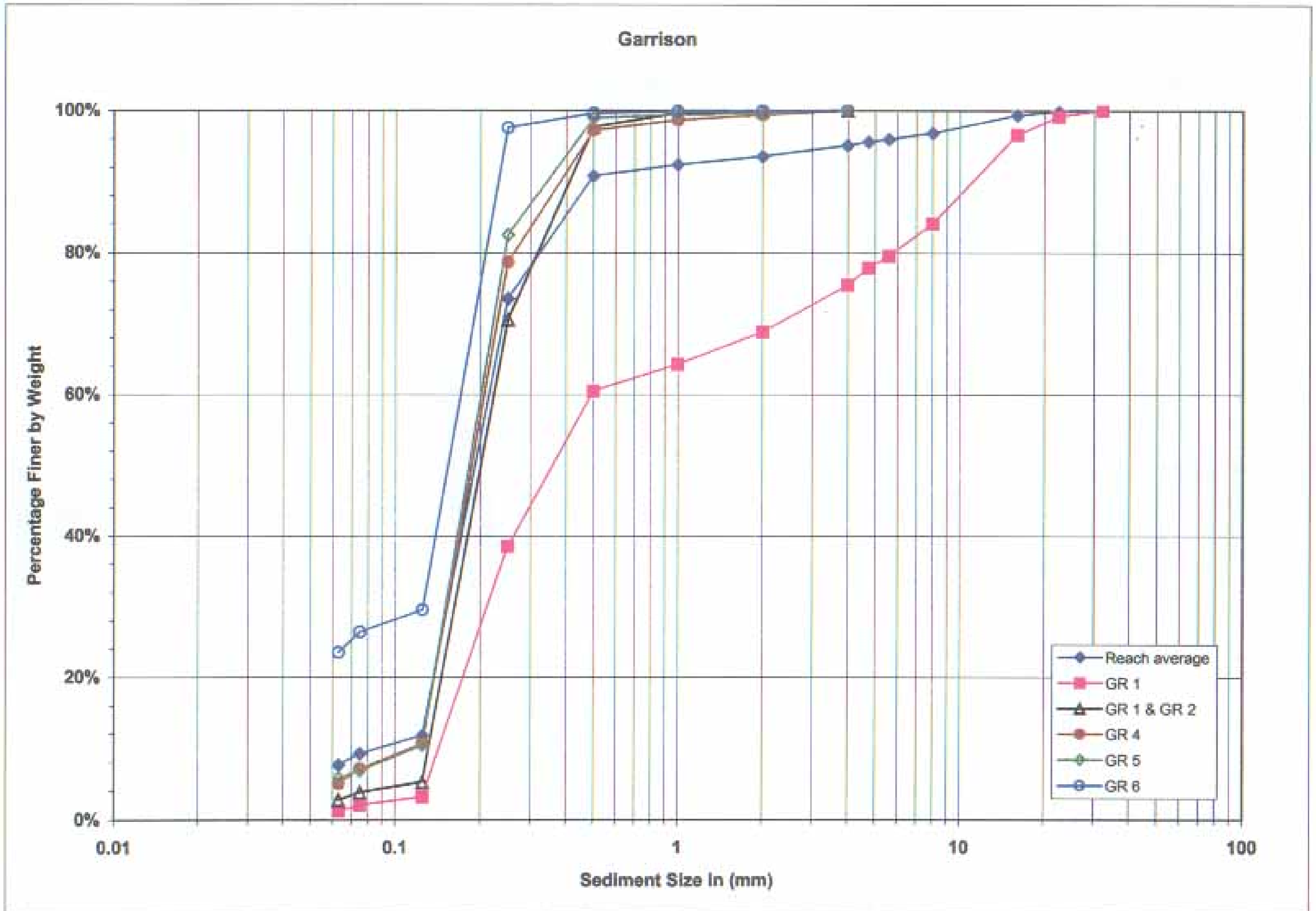


Figure 5.16 Average non-habitat bar gradation curves for individual geomorphic reaches and the reach average for the Garrison Reach.

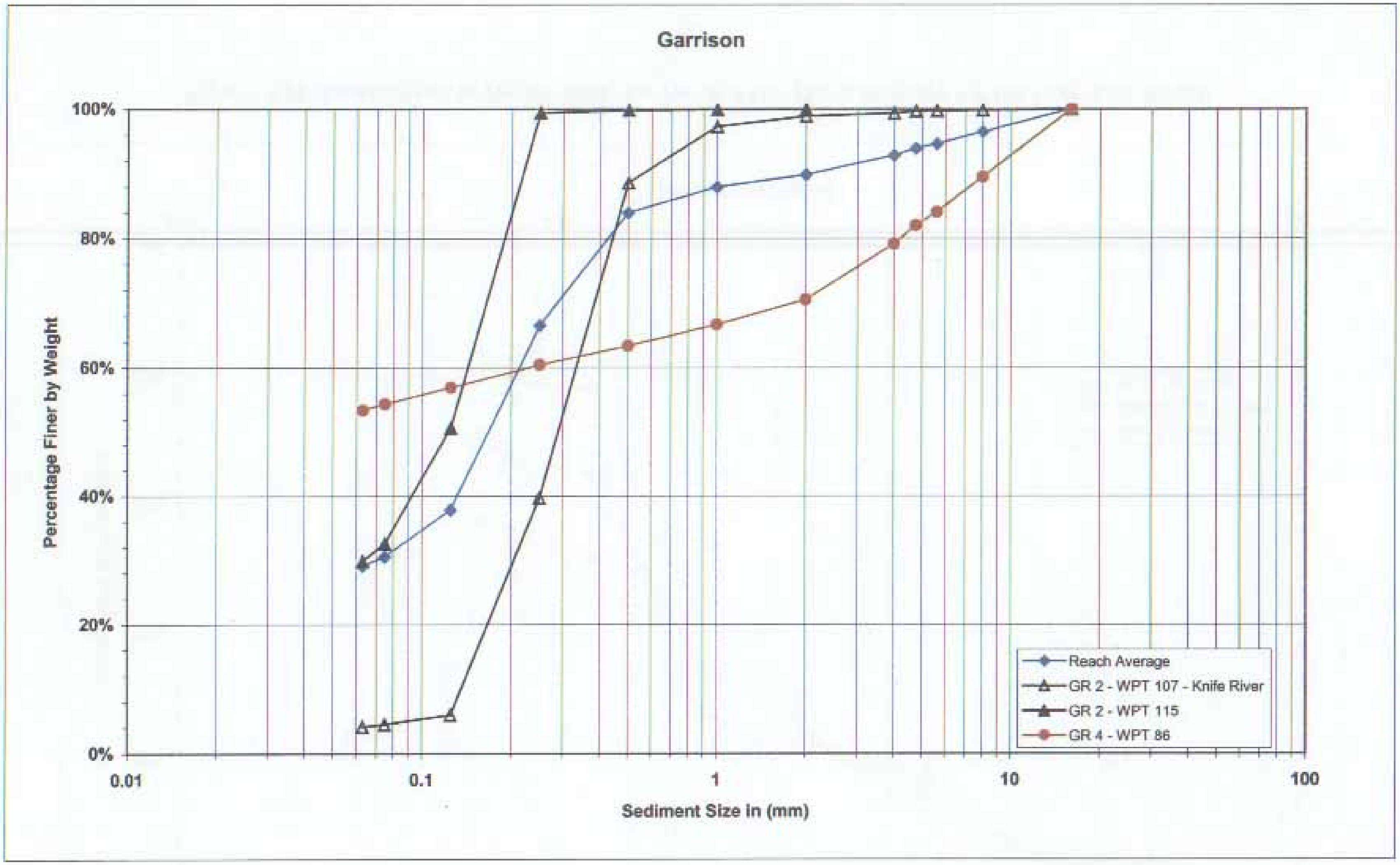


Figure 5.17 Gradation curves for each tributary and the reach average for the Garrison Reach.

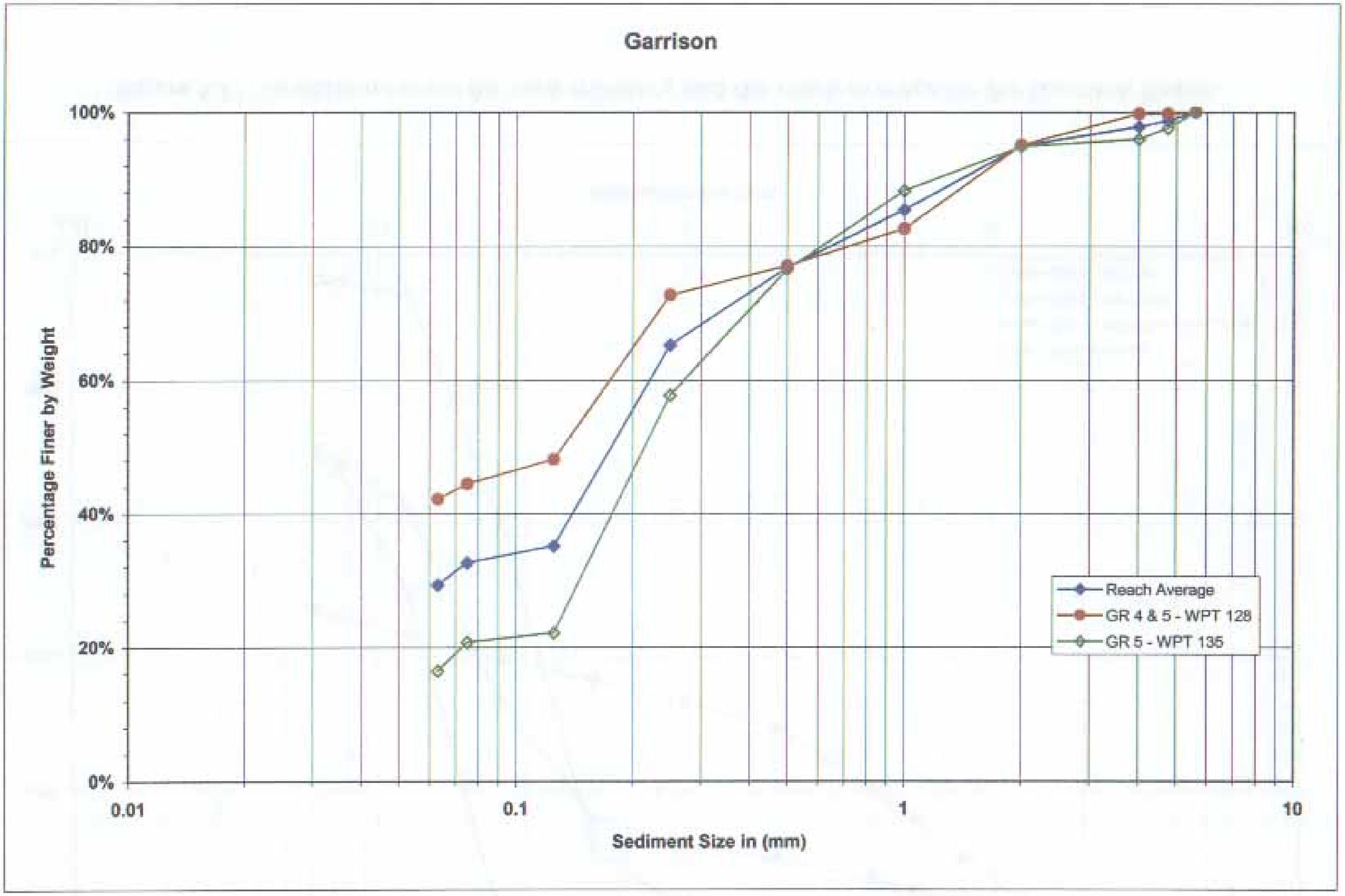


Figure 5.18 Gradation curves for each arroyo and the reach average for the Garrison Reach.

Table 5.9 Average bank gradation curves for each geomorphic reach in the Garrison Reach.

Geomorphic Reach (RM)	WPT	Grain Size (mm) Percent Finer by Weight															
		0.063	0.125	0.140	0.150	0.160	0.175	0.2	0.25	0.5	1	2	4	4.75	5.6	8	16
GR 1 (1388.5-1377.5)	90,91,92,93, 94,95,96,98, 99,100,102	12.15%	16.12%	24.00%	30.00%	34.00%	50.00%	62.00%	83.91%	97.36%	98.84%	99.91%	99.99%	100.00%			
GR 2 (1375.4-1364.3)	105,106,108, 109,110,111, 113,116,117, 118,119,120	25.16%	30.85%	36.00%	44.00%	47.00%	58.00%	68.00%	84.75%	98.45%	99.19%	99.80%	99.99%	100.00%			
GR 3 (1357.7-1355.3)	76,77,78,79, 80,81,123,124, 125	32.38%	44.40%	48.00%	54.00%	57.00%	68.00%	76.00%	90.80%	97.72%	99.35%	99.84%	99.99%	100.00%			
GRs 4, 5 & 6 (1346.6-1331.2)	87,88,89,126, 127,129,130, 133,134,136, 137	45.25%	51.15%	54.00%	60.00%	63.00%	72.00%	80.00%	92.85%	97.03%	98.57%	99.80%	99.93%	99.97%	99.98%	99.99%	100.00%

Figure 5.13 indicates that there is very little difference in the gradation of the habitat and non-habitat bars. Figures 5.13 also reveals that the banks are generally slightly finer than the bars. Examination of the samples taken near the mouths of tributaries and arroyos show considerable amounts of fines as well as some coarser material.

As indicated in Figure 5.13, there are essentially no fines (less than 0.063 mm) present in the bed. The average bed D_{10} value for the entire reach is about 0.20 mm (Table 5.8). As indicated in Table 5.8, the average D_{10} for the habitat bars is about 0.14 mm. This value corresponds to slightly less than the D_5 for the bed. This suggests for the Garrison Reach that material finer than about 0.14 mm is not in appreciable quantities in the bed and habitat bars. Therefore, sediment load composed of material greater than 0.14 mm may be considered bed material load while material finer than this behaves as wash load.

As shown in Table 5.9, the percent of the bank material finer than 0.063 mm ranged from about 12% to 45% with an average of about 29%. Thus, about 29% of the material eroded from the banks are fines (silts and clays) which are essentially nonexistent in the bed and habitat bars. The percent of the bank material coarser than 0.14 mm (corresponding to the bed and habitat bar material size in this reach) ranged from about 46% to 75% with an average of about 60%. Thus, for the Garrison Reach, about 60% of the material eroded from the banks is of the same size as the material found in appreciable quantities in the bed or habitat bars, and thus contributes to the bed material load.

5.2.5. Bank Erosion Analysis.

A summary of the total bank erosion results for the Garrison Reach is shown in Table 5.10. As indicated in Table 5.10, annual bank erosion rates per kilometer range from 5,593 m^3/yr/km in GR 5 to 10,869 m^3/yr/km in GR 6. The overall reach average rate is 7,323 m^3/yr/km.

5.2.6. Sediment Budget.

As discussed in Section 5.2.4, the bed material load in the Garrison Reach is comprised of material greater than about 0.14 mm. Therefore, the bank erosion volumes used in the Garrison sediment budget reflect the contribution of bank material greater than 0.14 mm. The sediment budget for the Garrison Reach is shown in Table 5.11. It should be noted that no data were available from Pokrefke *et al.* (1998) in GR 6. Therefore, the bed erosion and the bed and bank deposition values were approximated by assuming them to be equal to those immediately upstream in GR 5. As shown in Table 5.11, there is a general increase in bed material transport with distance downstream to about GR 3. Downstream of this, the transport remains relatively constant. Thus, the upstream segment of the Garrison Reach down to about GR 3 reflects a net erosional tendency while downstream of this reach the channel appears to be approaching dynamic equilibrium. These trends are generally comparable to the trends discussed in Section 5.2.1.

Table 5.10. Garrison bank erosion from 1980 to 1998.

Geomorphic Reach (RM)	Left Bank Erosion (m^3)	Right Bank Erosion (m^3)	Total Volume (m^3)	Annual Volume (m^3/yr)	Distance River (km)	Annual Volume/km (m^3/yr/km)
GR 1 (1390-1376)	2,262,223	1,059,746	3,321,969	184,554	22.5	8,193
GR 2 (1375-1363)	1,136,547	1,257,905	2,394,452	133,025	19.3	6,890
GR 3 (1362-1353)	957,965	879,411	1,837,376	102,076	14.5	7,049
GR 4 (1352-1340)	922,209	1,421,848	2,344,057	130,225	19.3	6,745
GR 5 (1339-1324)	1,169,237	1,260,373	2,429,610	134,978	24.1	5,593
GR 6 (1323-1315)	1,610,724	907,589	2,518,314	139,906	12.9	10,869
Total	8,058,905	6,786,873	14,845,777	824,765	112.6	7,323

Note: Total in column 7 is the total annual volume ÷ total river distance

Table 5.11 Garrison sediment budget with >0.14 mm bed material size.

Geomorphic Reaches (RM)	Erosion		Deposition		Net Sediment Transport from Erosion & Deposition (m^3/yr)	Upstream Sediment Supply (m^3/yr)	Sediment Transport Budget (m^3/yr)
	Bank (1980-1998) (m^3/yr)	Bed (1976-1985) (m^3/yr)	Bank (1976-1985) (m^3/yr)	Bed (1976-1985) (m^3/yr)			
GR 1 (1390-1376)	-140,353	-142,828	7,486	34,762	-240,932		-240,932
GR 2 (1375-1363)	-85,192	-411,339	28,852	142,302	-325,377	-240,932	-566,309
GR 3 (1362-1353)	-53,114	-72,115	104,450	114,648	93,869	-566,309	-472,441
GR 4 (1352-1340)	-59,943	-434,067	204,528	28,510	-260,972	-472,441	-733,413
GR 5 (1339-1324)	-62,131	-92,694	3,226	97,328	-54,270	-733,413	-787,683
GR 6 (1323-1315)	-64,399	-92,694*	3,226*	97,328*	-56,538	-787,683	-844,221
Total (1390-1315)	-465,132	-1,245,737	351,768	514,879	-844,221		

* No data available from Pokrefke *et al.* (1998), therefore, values from GR 5 were used in GR 6.

As a check, the bed material calculations performed herein were compared with the measured suspended sediment load at Bismarck, North Dakota. The average annual measured suspended load at Bismarck for the period 1972-1999 is about 2,115,000 m^3/yr. Since there are no gradation data for the measured suspended sediment at Bismarck, it was necessary to make some assumption concerning the sand load percentage of the total measured load. Forty percent was the value selected since this was the value measured for the Fort Peck Reach. Using this value, the estimated sand load is about 845,000 m^3/yr. The annual bed material load calculated in GRs 5 and 6 is about 800,000 m^3/yr. A direct comparison of these two values is not possible for two reasons: (1) the calculated sediment budget values reflect the bed material load (greater than 0.14 mm) and therefore should be somewhat less than the sand load which includes all sand sizes (greater than 0.062 mm); and (2) since the measured sand load does not include the unmeasured portion of the load, it should be less than the total bed material load calculated by the sediment budget. However, if it is assumed that these two factors tend to offset each other, then the two methods should produce values within about the same range. Based on this assumption it appears that the calculated bed material loads appear to be an acceptable range when compared to the measured suspended sand load data.

Table 5.12 shows the reduction in the supply of bed material sized sediment (greater than 0.14 mm) from bank erosion that would result from stabilization of 10% to 100% of the eroding areas for each of the GRs. As illustrated in Table 5.12, the impacts of bank stabilization vary from reach to reach. In GR 1, the banks contribute about 58% of the total bed material load in that reach. Therefore, if all bank erosion was eliminated by bank stabilization, there would be a reduction in the supply of bed material sized sediment in this reach of about 58%. As a consequence, the river would acquire this additional load from scouring the bed, bars, and/or remaining unprotected banks in the reach. In the other reaches, the bank contributions range from about 8% to 15%. Therefore, the sediment transport impacts associated with bank stabilization in these reaches should be less. Table 5.12 also allows for the determination of the impacts associated with only stabilizing some of the eroding areas. For instance, in GR 1, if 20% of the eroding areas were stabilized, there would be about a 12% reduction in the supply of bed material sized sediment to the reach. However, if 50% of the eroding areas were stabilized, the reduction would be almost 29%.

Table 5.12 also shows the reach average values for the entire Garrison Reach. Considering the entire Garrison Reach, the banks supply about 13% of the bed material load. Thus, on a gross reach level, the effects of stabilizing all eroding areas would reduce the supply of bed material by about 13%.

Table 5.12 Bank stabilization impact on the Garrison Reach.

Garrison budget with >0.14 mm bed material size.

Revetment Percentage	Geomorphic Reaches: Reduction of Bank Contribution GR 1 RM 1390- RM 1376	Reduction of Bank Contribution GR 2 RM 1375- RM 1363	Reduction of Bank Contribution GR 3 RM 1362- RM 1353	Reduction of Bank Contribution GR 4 RM 1352- RM 1340	Reduction of Bank Contribution GR 5 RM 1339- RM 1324	Reduction of Bank Contribution GR 6 RM 1323- RM 1315	Reach Average Reduction of Bank Contribution RM 1390 – RM 1315
10	6%	2%	1%	1%	1%	1%	1%
20	12%	3%	2%	2%	2%	2%	3%
30	17%	5%	3%	2%	2%	2%	4%
40	23%	6%	4%	3%	3%	3%	5%
50	29%	8%	6%	4%	4%	4%	6%
60	35%	9%	7%	5%	5%	5%	8%
70	41%	11%	8%	6%	6%	5%	9%
80	47%	12%	9%	7%	6%	6%	10%
90	52%	14%	10%	7%	7%	7%	11%
100	58%	15%	11%	8%	8%	8%	13%

5.2.7. Discussion of Results.

When the banks in the Garrison Reach are compared to the bars, it is found that the bars are generally somewhat coarser than the banks. Habitat and non-habitat bars in the Garrison Reach had very similar gradations. The habitat bars in this reach are composed almost entirely of sand sized material with the average D_{10} being about 0.14 mm. The channel bed is slightly coarser than the habitat bars with an average D_{10} of about 0.20 mm. A grain size of 0.14 mm was selected to represent the lower size limit of material found in appreciable quantities in the bed and habitat bars for this reach. The percent of bank material coarser than 0.14 mm ranged from about 46% to 76% with an average of about 60%. This suggests that for the Garrison Reach, about 60% of the material eroded from the banks is of the same size found in appreciable quantities in the bed or habitat bars.

The sediment budget for the Garrison Reach suggests that the upper portion of the reach extending downstream to the vicinity of GR 3 exhibits erosional tendencies while the downstream reach appears to be approaching a state of dynamic equilibrium. The total annual volume of material eroded from the channel banks in the Garrison Reach is about 825,000 m^3/yr, or about 7,000 m^3/yr/km. While this is a large number, it must be remembered that about 60% of this material contributes to the bed material load in the reach. Therefore, the overall contribution from bank erosion to the bed material load in the Garrison Reach is only about 13%. However, at the reach scale, the material supplied from bank erosion in GR 1 represents about 58% of the total bed material load. The smallest bank contributions to the bed material load occurred in GRs 4, 5, and 6, with only about 8% in each.

The Garrison Reach has a considerable amount of bank stabilization in it, with the percent of total bank line in the GRs that is stabilized ranging from about 9% to 36%. Therefore, an attempt was made to determine if there was a relationship between percent of bankline stabilized and changes in bar density. However, after a careful examination of the data, no definitive relationships could be discerned. A complicating factor in this analysis was that the latest photography (1997) was flown at a discharge about 4 to 5 time greater than the previous two periods. Heavily stabilized reaches exhibited both increases and decreases in bar and island density. While these results were inconclusive, they do seem to suggest that there are multiple controlling factors affecting the morphology of the bars and islands. A more focused and extensive research effort would be required to try and identify these multiple controlling factors.

The supply of suitably sized sediment from the banks is just one factor that may influence bar morphology. Another factor that is very important is the local geometry of the reach. This analysis revealed a strong relationship between channel width and the presence or absence of bars. Reaches with bars and islands present were much wider than reaches without bars. The mean channel width for reaches where no bars were visible was about 534 m, while in the reaches with bars and islands, the mean widths were about 693 m and 860 m, respectively. Seventy five percent of the reaches with no bars present had a channel width less than 631 m, while only 35% of reaches with bars, and 17% of reaches with islands had channel widths less than 631 m. Therefore, a channel width in the range of about 630 m appears to be a threshold zone below which it is very unlikely that bars will exist. While the relationship between channel width and the presence of bars and islands was not quite as strong as in the Fort Peck Reach, it still appears to be one of the dominant factors with respect to bar and island formation. Recognition of the relationship between channel width and bar morphology is important for the effective management of this system to minimize impacts to channel bars.

It should be remembered that as with any sediment transport analysis, there is considerable uncertainty in these results. Consequently, the results presented herein do not represent absolute values, but rather, should be viewed as providing a reasonable approximation of the general trends in the reach.

5.3. Fort Randall Reach

5.3.1. General Characteristics of the Fort Randall Reach.

The Fort Randall study reach extends from River RM 880, just downstream of the Fort Randall Dam to the confluence with the Niobrara River at RM 844 (Figure 5.19). This reach is regulated by the Fort Randall Dam, which was constructed between 1946 and 1953 by the USACE. The mean annual flow in the Fort Randall Reach is about 801 CMS. Bed material in the reach is predominately sand with occasional outcrops of gravel. The channel in this reach is essentially straight with sinuosity ranging from about 1.0 to 1.02. Most reaches exhibit a moderate to high degree of braiding with numerous bars and islands. The channel widths ranged from about 300 m to 2,270 m with an average width of about 820 m. The energy slope for the Fort Randall Reach, calculated from the HEC-RAS analysis, ranges from about 0.00006 to 0.00012. Minor tributaries, both gauged and ungauged, contribute <3% of the total reach flow. Ponca Creek and Choteau Creek are examples of such tributaries. The largest tributary in this reach is the Niobrara River which enters at the downstream limit of the study reach. The Fort Randall Reach is characterized by high bluffs throughout the reach. Bank heights in this reach generally range from about 3 to 15 m with an average bank height of about 7 m. For this study the Fort Randall Reach was divided into six GRs.

The specific gauge records for the Fort Randall Reach are shown in the Appendix C of the data supplement CD ROM. The period of record for the main stem Missouri River gauges generally extends through the mid to late 1980s. The Ponca Creek and Niobrara River gauges have data through the late 1990s. Based on the gauge records, it appears that the upstream portion of the reach may have exhibited a slight degradational trend through the early 1980s, and then has begun to stabilize. According to Dangberg *et al.* (1988) the reach from about RM 860 to RM 853 represents the transition zone between degradation upstream and aggradation downstream.

5.3.2. Relationship Between Channel Width and Bars and Islands.

The cumulative distribution relating channel width and the occurrence of bars and islands for two time periods, 1976 and 1997, are shown in Figure 5.20. Box and whisker plots for the data are shown in Figures 5.21. As indicated in Figure 5.20 the width of the channel in reaches with no bars is only slightly less than the reaches with bars. For instance, the mean width for the reaches with 'no bars' in 1998 was about 624 m while the reaches with 'bars' had a mean width

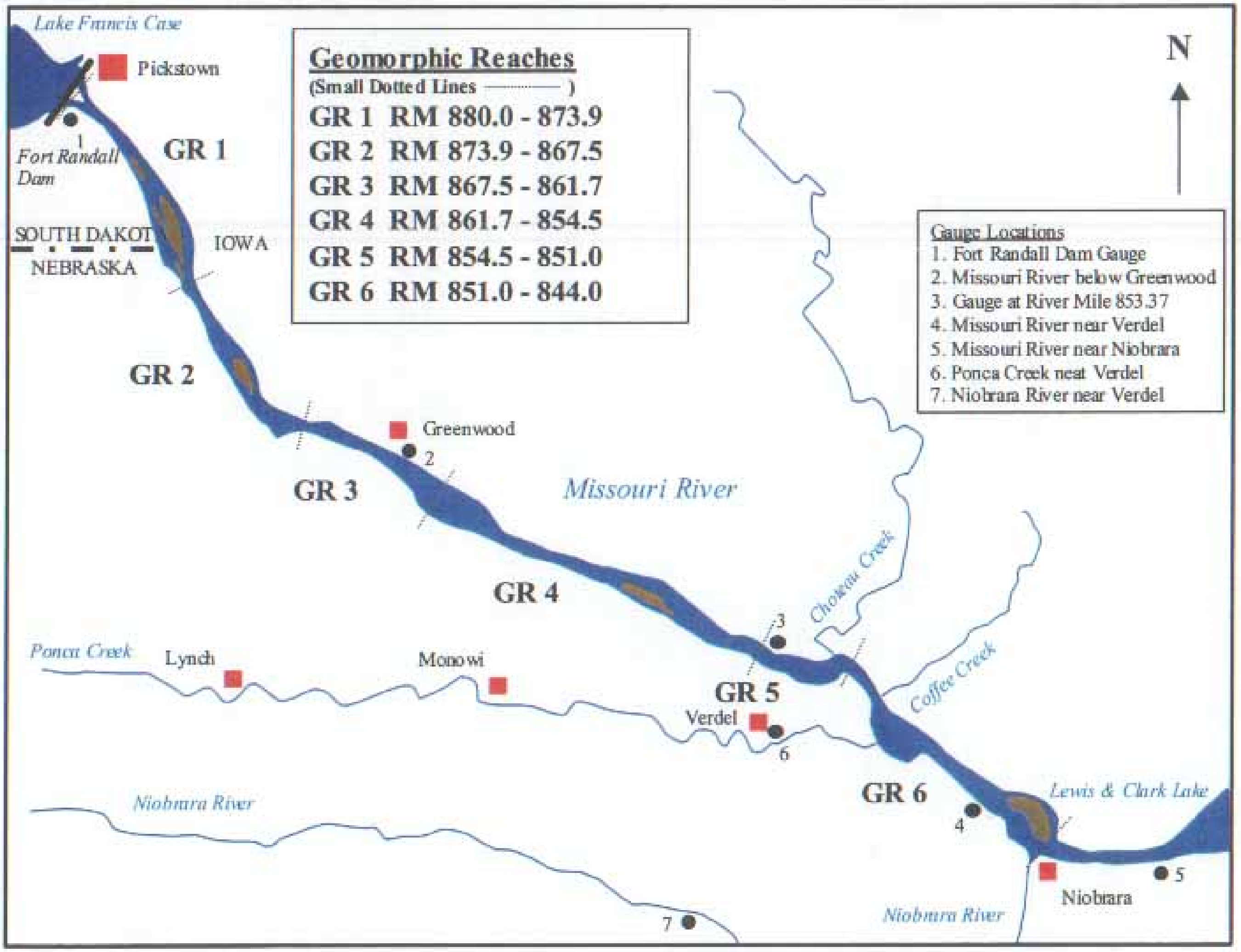
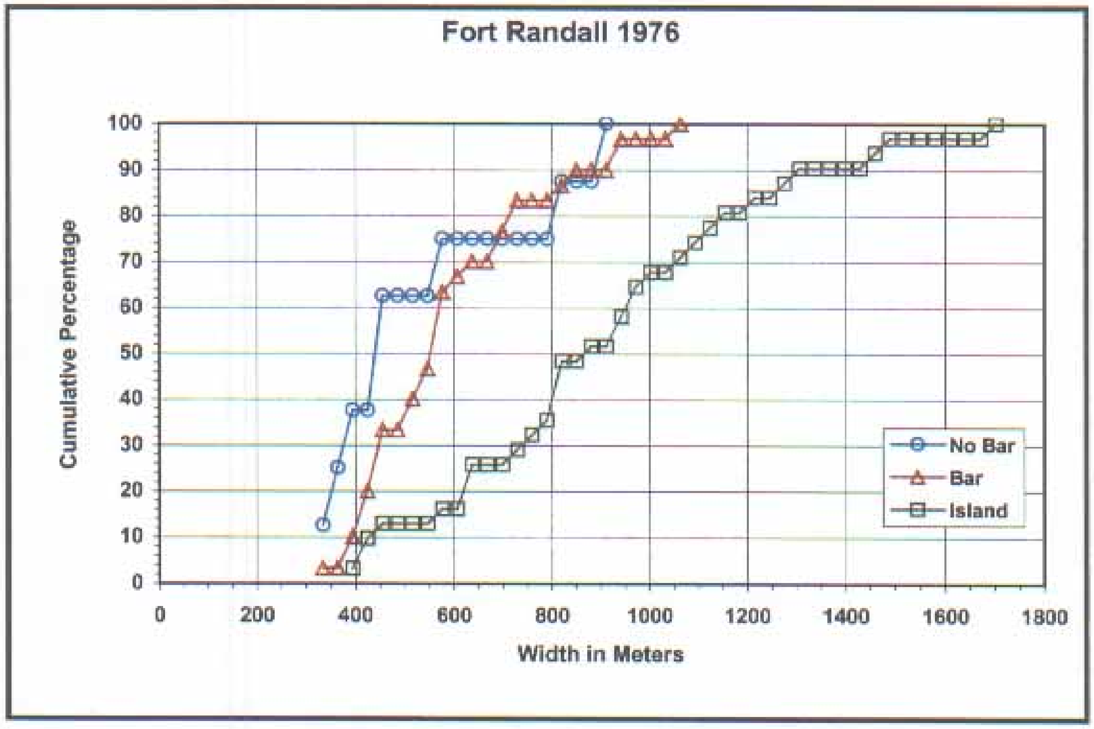


Figure 5.19 Vicinity map for the Fort Randall Reach.



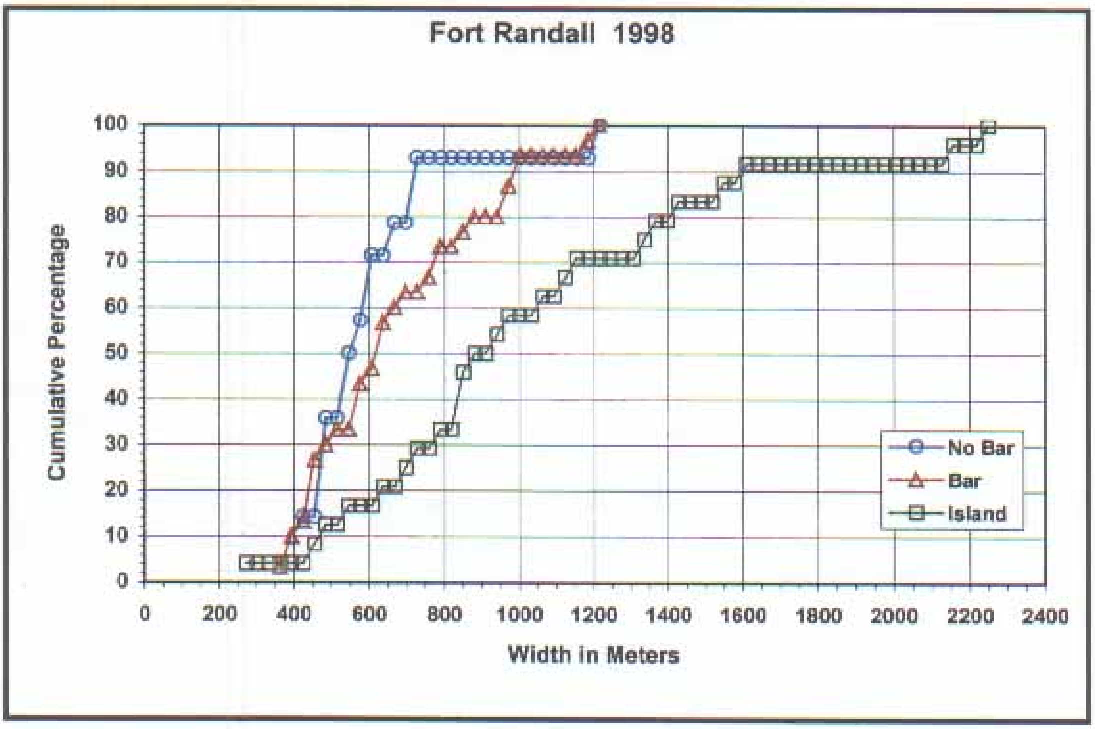


Figure 5.20 Cumulative distribution of channel width and occurrence of bars and islands for 1976 and 1998, for the Fort Randall Reach.

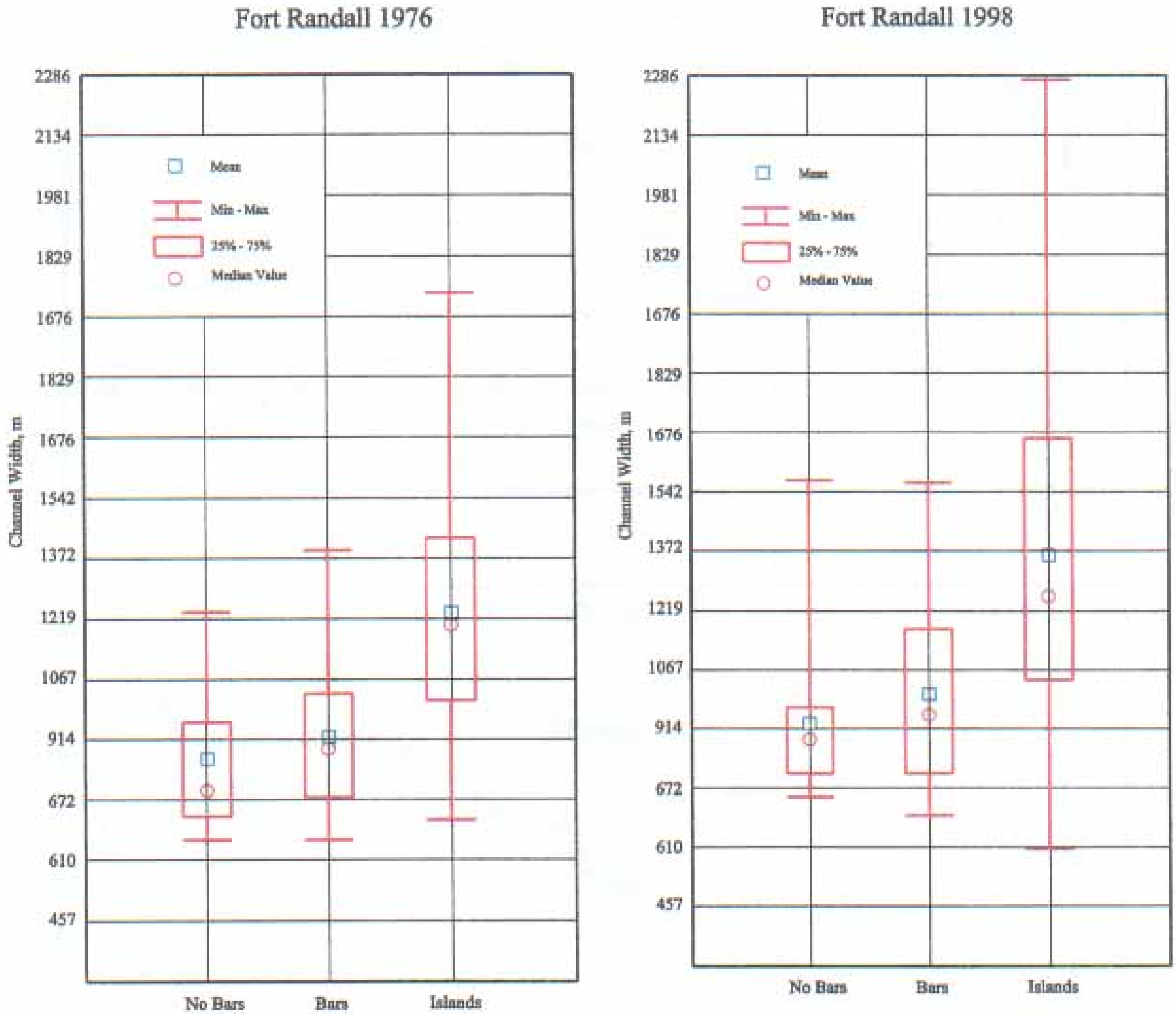


Figure 5.21 Box and whisker plots displaying the cumulative distribution of channel width and occurrence of bars and islands for 1976 and 1998, for the Fort Randall Reach.

of about 700 m. The mean channel width for the islands was much larger at about 1,058 m. In the reaches with 'no bars', 75% of the widths were less than 665 m, while the corresponding width in the reaches with 'bars' was 867 m. Thus, while there does appear to be a relationship between channel width and the presence of bars and islands in the Fort Randall Reach, it does not appear to be as strong as in the Fort Peck, Garrison, or Gavins Point Reaches. Therefore, it is difficult to establish a threshold value between reaches with 'bars' and 'no bars'. One explanation for this is that because of the highly braided character of the Fort Randall Reach, there were very few reaches where no bars were visible. It was also extremely difficult to establish a reasonable channel width in the lower portions of the study reach where the river is highly braided.

5.3.3. Bar and Island Density Analysis.

The results of the bar and island density analysis for the Fort Randall Reach are shown in Table 5.13. As shown in Table 4.16 the dates of the aerial photography and the associated discharges were October 17,1976 (1,076 CMS), May 4, 1994 (835 CMS), August 28, 1998 (801 CMS), and August 29, 1998 (818 CMS). Thus, the discharge range for all time periods was similar. While the island and bar density did increase in a few reaches, the predominate trend between 1976 and 1998 was decreasing (Table 5.13). Table 5.13 also shows the percent of bank line that is stabilized for each reach. Stabilization percentages range from about 0% to 33%. For the entire reach, about 12.5% of the bank lines are stabilized. Although most of the reaches experienced decreases in bar and island density, some of the most dramatic decreases occurred in non-stabilized reaches. Thus, it is difficult to establish any trends in bar or island density related to percent of bank line stabilized.

Table 5.13 Island and sandbar density and percent of bank line stabilized for the Fort Randall Reach.

	Fort Randall Reach, Island and Sandbar Density						Aerial Mosaic June 1, 1982		
	1960 RM		Reach Length (km)	Density (ha/km)			Percent of Reach Revetted		
	Upstream	Downstream		As of 1976	As of 1994	As of 1998	Left	Right	Total
Islands	880	878	3.2	2.4	4.8	-	0.0	37.9	19.0
	878	873	8.0	37.5	31.3	25.2	0.0	66.3	33.1
	873	868	8.0	29.5	35.2	0.0	20.5	9.8	15.2
	868	863	8.0	0.0	0.0	0.0	0.0	33.3	16.7
	863	858	8.0	166.2	95.1	1.4	0.0	0.0	0.0
	858	853	8.0	68.4	67.1	79.1	0.0	40.1	20.1
	853	848	8.0	44.1	25.9	39.1	0.0	0.0	0.0
	848	843	8.0	76.4	52.0	97.1	0.0	0.0	0.0
	Entire Reach Average			52.6	40.6	34.6	-	-	-
Sandbars	880	878	3.2	0.1	0.0	-	0.0	37.9	19.0
	878	873	8.0	11.9	3.8	6.9	0.0	66.3	33.1
	873	868	8.0	6.5	3.5	11.8	20.5	9.8	15.2
	868	863	8.0	32.5	2.7	12.0	0.0	33.3	16.7
	863	858	8.0	81.7	0.3	1.6	0.0	0.0	0.0
	858	853	8.0	26.0	0.1	5.5	0.0	40.1	20.1
	853	848	8.0	52.6	2.2	10.2	0.0	0.0	0.0
	848	843	8.0	34.4	10.2	8.4	0.0	0.0	0.0
	Entire Reach Average			30.0	3.5	8.0	-	-	-

5.3.4. Sediment Gradation Analysis.

Figure 5.22 shows the reach average gradation curves in the Fort Randall Reach for the habitat bars, non-habitat bars, distributary delta bar, tributary bars, arroyos, banks, and channel bed. The D_{10}, D_{50}, and D_{90} values for these features are shown in Table 5.14. The individual gradation curves for the banks, habitat bars, non-habitat bars, and arroyos are shown in Figures 5.23, 5.24, 5.25, and 5.26, respectively.

Table 5.15 presents the average bank gradation curves that were developed to represent each geomorphic reach in the Fort Randall Reach. These data are also shown graphically in Figure 5.23. As indicated in Table 5.15, three gradation curves were used to represent the Fort Randall Reach. One single curve was used for GRs 1, 2, and 3; GRs 4 and 5; and GR 6. The gradation curves for the habitat bars in the Fort Randall Reach are shown in Figure 5.24. As shown in Figure 5.24 there are essentially no fines (less than 0.063 mm) found in the habitat bars.

Figure 5.25 indicates that the non-habitat bars are slightly finer than the habitat bars, and that the banks are considerably finer than the bars. Figure 5.22 also shows that the bed is slightly coarser than the bars. The only sample taken near the mouth of an arroyo shows a considerable amount of fines as well as some coarse material. As indicated in Figure 5.22 there are essentially no fines (less than 0.063 mm) present in the bed. The average bed D_{10} value for the entire reach is about 0.21 mm (Table 5.14). As indicated in Table 5.14, the average D_{10} for the habitat bars is about 0.16 mm. This value corresponds to slightly less than the D_5 for the bed. This suggests for the Fort Randall Reach that material finer than about 0.16 mm is not found in appreciable quantities in the bed and habitat bars. Therefore, sediment load composed of material greater than 0.16 mm may be considered bed material load while material finer than this behaves as wash load.

As shown in Table 5.15, the percent of the bank material finer than 0.063 mm ranged from about 58% to 79% with an average of about 66%. Thus, about 66% of the materials eroded from the banks are fines (silts and clays), which are essentially nonexistent in the bed and habitat bars. The percent of the bank material coarser than 0.16 mm ranged from about 11% to 28% with an average of about 21%. Thus, for the Fort Randall Reach, about 21% of the material eroded from the banks is of the same size as the material found in appreciable quantities in the bed or habitat bars, and thus contributes to the bed material load.

5.3.5. Bank Erosion Analysis.

A summary of the total bank erosion results for the Fort Randall Reach is shown in Table 5.16. As indicated in Table 5.16, annual bank erosion rates per kilometer range from 9,432 m^3/yr/km in GR 4 to 23,578 m^3/yr/km in GR 3. The overall reach average rate is 14,455 m^3/yr/km.

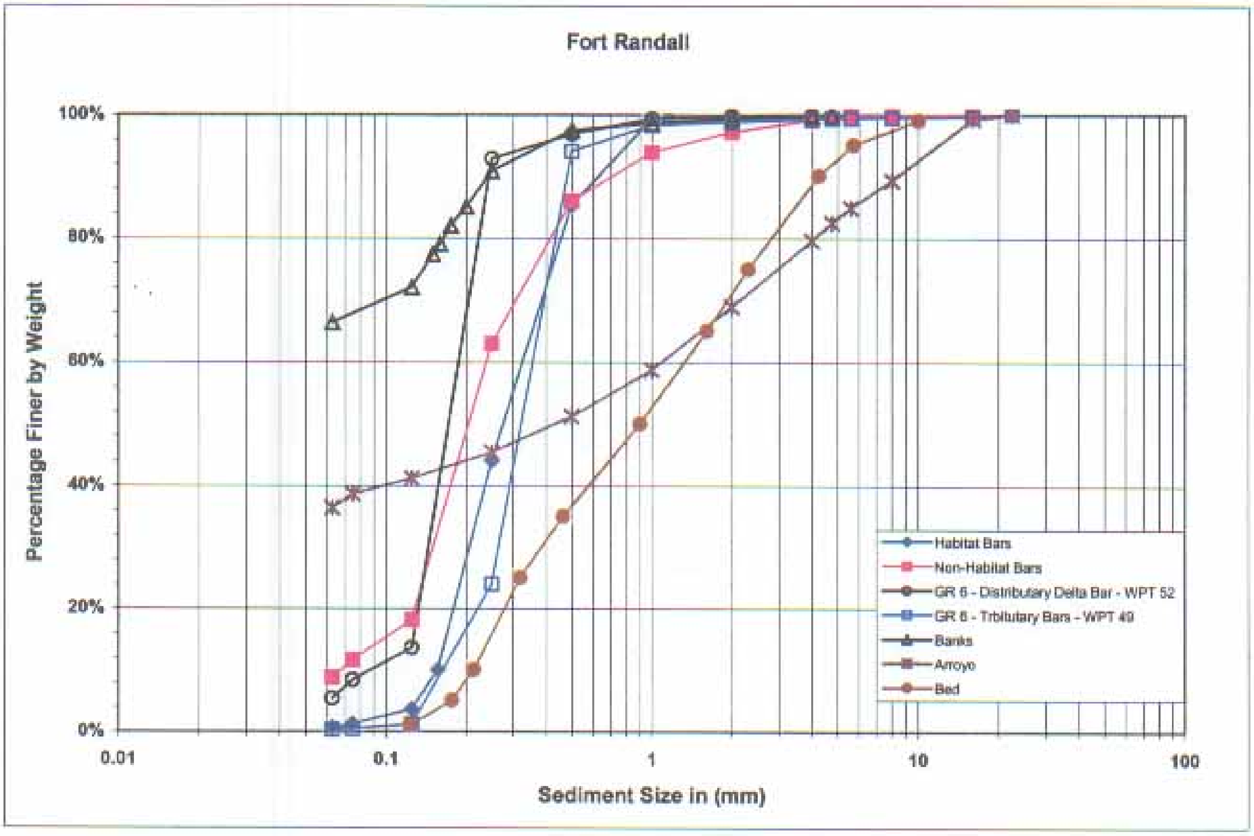


Figure 5.22 Reach average gradation curves for the habitat bars, non-habitat bars, distributary delta bar, tributary bars, arroyos, banks, and channel bed for the Fort Randall Reach.

Table 5.14 Fort Randall Reach average D_{10}, D_{50} and D_{90} values for habitat bars, non-habitat bars, distributary delta bar, tributary bars, arroyos, banks, and channel bed.

Percent	Reach Average Habitat Bar (mm)	Reach Average Non-Habitat Bar (mm)	Reach Average Distributary Delta Bar (mm)	Reach Average Tributary (mm)	Reach Average Arroyo (mm)	Reach Average Banks (mm)	Reach Average Bed (mm)
D_{10}	0.16	0.07	0.09	0.16	-	-	0.21
D_{50}	0.28	0.20	0.17	0.32	0.44	-	0.90
D_{90}	0.63	0.71	0.24	0.48	8.42	0.24	4.25

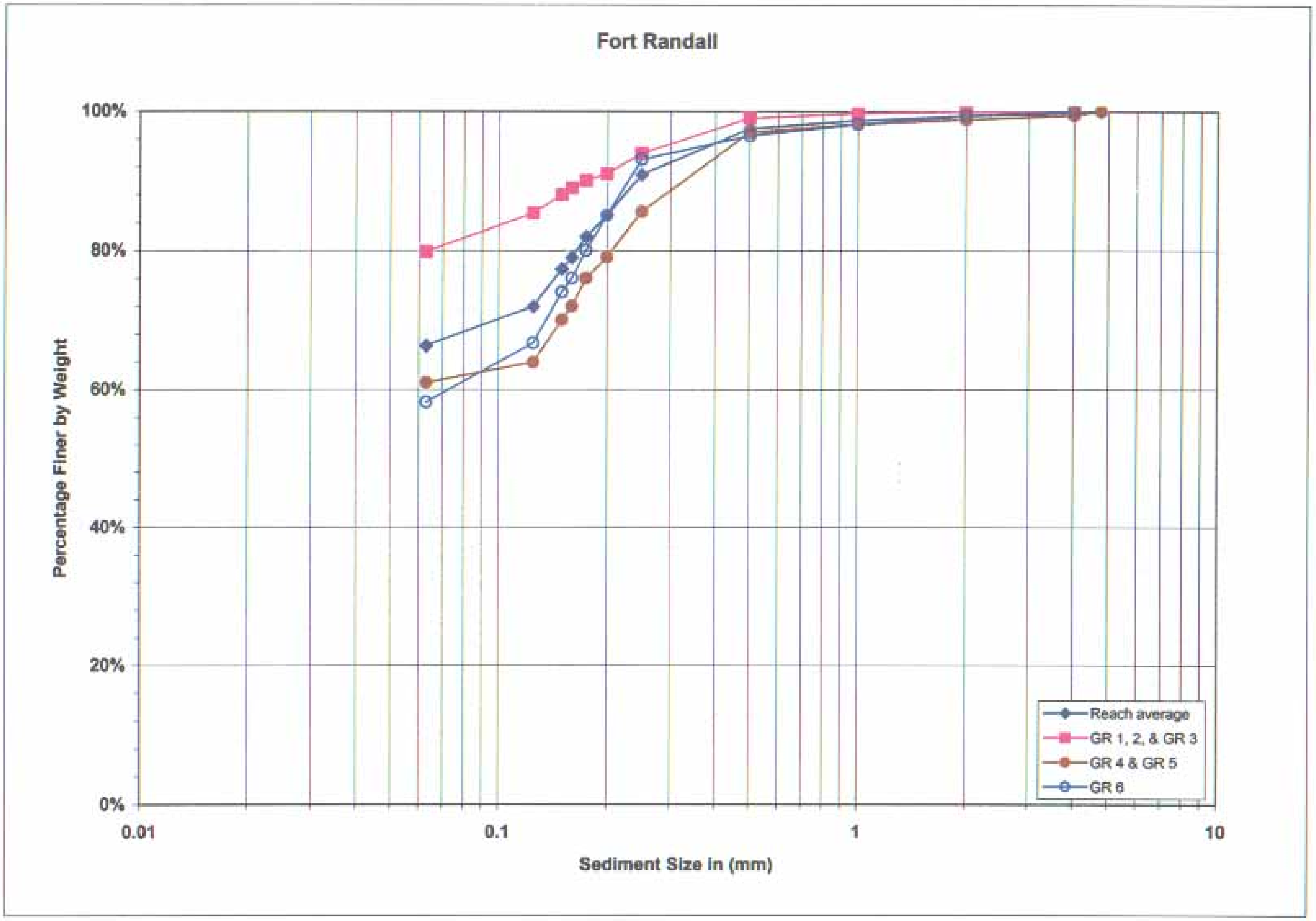


Figure 5.23 **Average bank gradation curves for individual geomorphic reaches and the reach average for the Fort Randall Reach.**

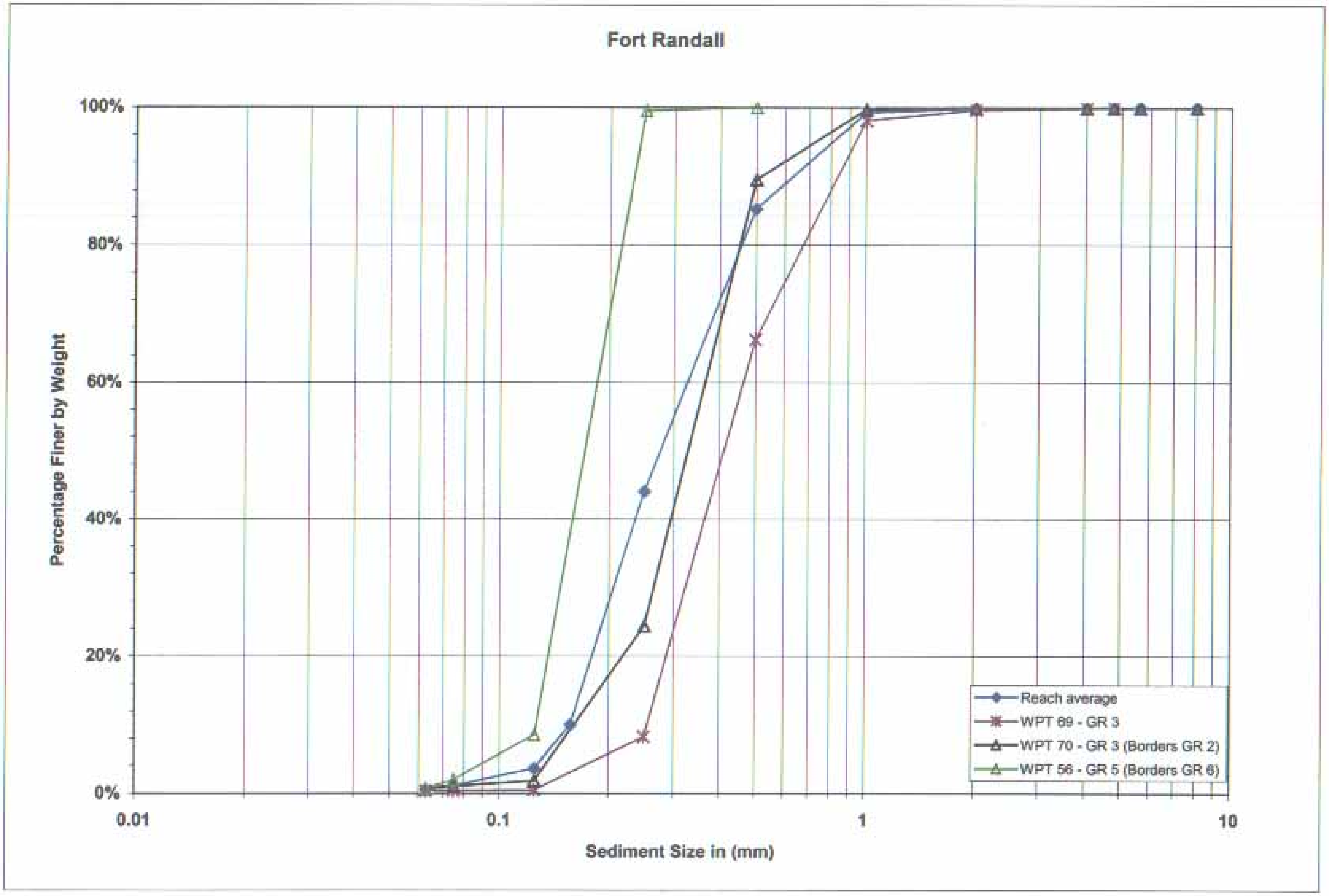


Figure 5.24 Gradation curves for each habitat bar and the reach average for the Fort Randall Reach.

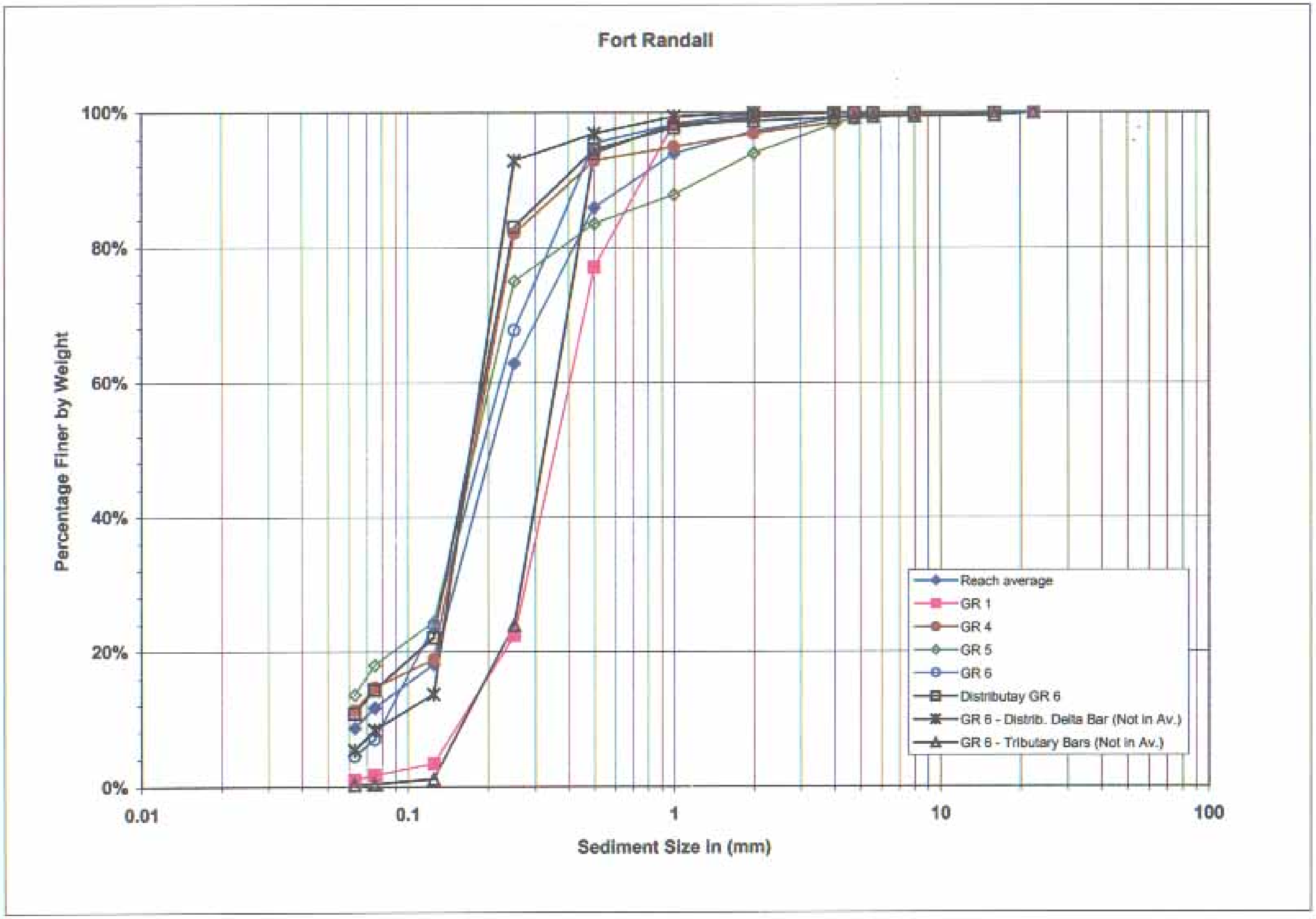


Figure 5.25 Average non-habitat bar gradation curves for individual geomorphic reaches and the reach average for the Fort Randall Reach.

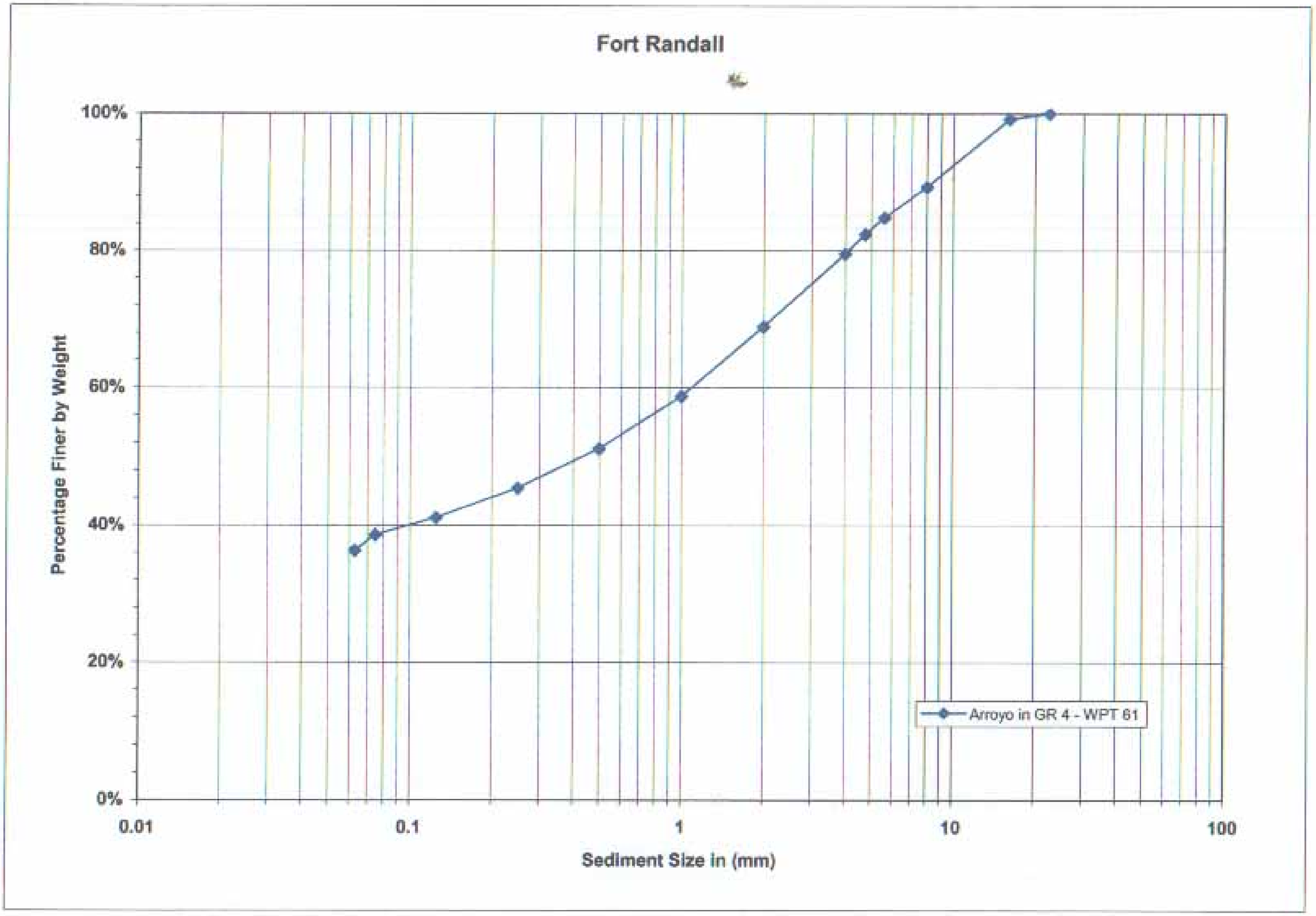


Figure 5.26 Gradation curve for an arroyo for the Fort Randall Reach.

Table 5.15 Average bank gradation curves for each geomorphic reach in the Fort Randall Reach.

Geomorphic Reach (RM)	WPT	Grain Size (mm) Percent Finer by Weight															
		0.063	0.125	0.14	0.150	0.160	0.175	0.2	0.25	0.5	1	2	4	4.75	5.6	8	16
GRs 1, 2 & 3 (876.6-863.2)	68,71,72,75	79.81%	85.36%	86.00%	88.00%	89.00%	90.00%	91.00%	93.96%	99.03%	99.70%	99.94%	100.00%				
GRs 4 & 5 (859.4-853.0)	59,64,65	60.97%	63.89%	66.00%	70.00%	72.00%	76.00%	79.00%	85.58%	96.97%	98.11%	98.84%	99.44%	100.00%			
GR 6 (850.5-849.9)	53,54	58.17%	66.70%	70.00%	74.00%	76.00%	80.00%	85.00%	93.03%	96.44%	98.13%	99.35%	100.00%				

Table 5.16 Fort Randall bank erosion from 1976 to 1998.

Geomorphic Reach (RM)	Left Bank Erosion (m^3)	Right Bank Erosion (m^3)	Total Volume (m^3)	Annual Volume (m^3/yr)	Distance River (km)	Annual Volume/km (m^3/yr/km)
GR 1 (879-773)	1,528,102	814,002	2,342,104	106,459	9.7	11,027
GR 2 (872-867)	1,463,281	362,211	1,825,492	82,977	8.0	10,314
GR 3 (866-861)	1,655,688	2,517,367	4,173,055	189,684	8.0	23,578
GR 4 (860-854)	890,417	1,112,884	2,003,301	91,059	9.7	9,432
GR 5 (853-851)	436,569	561,724	998,294	45,377	3.2	14,101
GR 6 (850-843)	1,773,850	2,746,093	4,519,943	205,452	11.3	18,241
Total	7,747,908	8,114,281	15,862,189	721,009	49.9	14,455

Note: Total in column 7 is the total annual volume ÷ total river distance

5.3.6. Sediment Budget.

As discussed in Section 5.3.4, the bed material load in the Fort Randall Reach is comprised of material greater than about 0.16 mm. Therefore, the bank erosion volumes used in the Fort Randall sediment budget reflect the contribution of bank material greater than 0.16 mm. The sediment budget for the Fort Randall Reach is shown in Table 5.17. As shown in Table 5.17, GR 1 is a net degradational reach while GR 2 is slightly aggradational. A degradational trend is once again reflected in GR 3. Downstream of GR 3 the river appears to have stabilized with a slight aggradational tendency in GR 6. These trends are reasonably consistent with the trends discussed in Section 5.3.1, with slight degradation in the upper reaches transitioning to dynamic equilibrium in the middle reaches and aggradation in the lower reaches.

Table 5.18 shows the reduction in the supply of bed material sized sediment (greater than 0.16 mm) from bank erosion that would result from stabilization of 10% to 100% of the eroding areas for each of the GRs. As illustrated in Table 5.18, the impacts of bank stabilization vary from reach to reach, but are generally slightly less than in the other three study reaches. The highest contribution of bed material sized sediment occurs in GR 6 with the banks contributing about 13% of the bed material load. Therefore, if all bank erosion was eliminated by bank stabilization, there would be a reduction in the supply of bed material sized sediment in this reach of about 13%. As a consequence, the river would acquire this additional load from scouring the bed, bars, and/or remaining unprotected banks in the reach. In the other reaches, the bank contributions range from about 3% to 11%. Therefore, the sediment transport impacts associated with bank stabilization in these reaches should be less. Table 5.18 also allows for the determination of the impacts associated with only stabilizing some of the eroding areas. For instance, in GR 6, if 50 percent of the eroding areas were stabilized, there would be about a 6% reduction in the supply of bed material sized sediment to the reach.

Table 5.17 Fort Randall sediment budget with >0.16 mm bed material size.

Geomorphic Reaches (RM)	Erosion: Bank (1976-1998) (m^3/yr)	Erosion: Bed (1975-1985) (m^3/yr)	Deposition: Bank (1975-1985) (m^3/yr)	Deposition: Bed (1975-1985) (m^3/yr)	Net Sediment Transport from Erosion & Deposition (m^3/yr)	Upstream Sediment Supply (m^3/yr)	Sediment Transport Budget (m^3/yr)
GR 1 (879-873)	-11,718	-95,378	53		-107,043		-107,043
GR 2 (872- 867)	-9,133	-52,559	51,940	26,676	16,923	-107,043	-90,120
GR 3 (866- 861)	-20,879	-161,949	2,229	15,223	-165,375	-90,120	-255,495
GR 4 (860-854)	-25,513	-127,096	5,161	22,130	-125,318	-255,495	-380,813
GR 5 (853-851)	-12,714	0	5,947	1,185	-5,582	-380,813	-386,395
GR 6 (850- 843)	-49,341	-138,901	69,616	134,812	16,186	-386,395	-370,210
Total (879-843)	-129,298	-575,884	134,946	200,026	-370,210		

Table 5.18 Bank stabilization impact on the Fort Randall Reach.

Fort Randall budget with >0.16 mm bed material size.

Revetment Percentage	Geomorphic Reaches: Reduction of Bank Contribution GR 1 RM 878-RM873	Reduction of Bank Contribution GR 2 RM 872-RM 867	Reduction of Bank Contribution GR 3 RM 866-RM 861	Reduction of Bank Contribution GR 4 RM 860-RM 854	Reduction of Bank Contribution GR 5 RM 853-RM 851	Reduction of Bank Contribution GR 6 RM 850-RM 843	Reach Average Reduction of Bank Contribution RM 879-RM 843
10	1%	1%	1%	1%	0%	1%	1%
20	2%	2%	2%	1%	1%	3%	2%
30	3%	3%	2%	2%	1%	4%	2%
40	4%	4%	3%	3%	1%	5%	3%
50	5%	5%	4%	3%	2%	7%	4%
60	7%	6%	5%	4%	2%	8%	5%
70	8%	7%	6%	5%	2%	9%	6%
80	9%	8%	7%	5%	3%	11%	7%
90	10%	9%	7%	6%	3%	12%	7%
100	11%	10%	8%	7%	3%	13%	8%

Table 5.18 also shows the reach average values for the entire Fort Randall Reach. Considering the entire Fort Randall Reach, the banks supply about 8% of the bed material load. Thus, on a gross reach level, the effects of stabilizing all eroding areas would reduce the supply of bed material sized sediment by only about 8%.

5.3.7. Discussion of Results.

When the banks in the Fort Randall Reach are compared to the bars, it is found that the bars are generally much coarser than the banks. Habitat bars in the Fort Randall Reach are slightly coarser than the non-habitat bars. The habitat bars in this reach are composed almost entirely out of sand sized material with the average D_{10} being about 0.16 mm. The channel bed is slightly coarser than the habitat bars with an average D_{10} of about 0.21 mm. A grain size of 0.16 mm was selected to represent the lower size limit of material found in appreciable quantities in the bed and habitat bars for this reach. The percent of bank material coarser than 0.16 mm ranged from about 11% to 28% with an average of about 21%. This suggests that for the Fort Randall Reach, about 21% of the material eroded from the banks is of a size that is found in appreciable quantities in the bed and habitat bars.

The sediment budget for the Fort Randall Reach suggests that the upper portion of the reach extending downstream to the vicinity of GR 3 exhibits degradational tendencies while the downstream reach transitions from dynamic equilibrium to slight aggradation. The total annual volume of material eroded from the channel banks in the Fort Randall Reach is about 721,000 m^3/yr, or about 14,000 m^3/yr/km. While this is a large number, it must be remembered that only about 21% of this material contributes to the bed material load in the reach. Therefore, the overall contribution from bank erosion to the bed material load in the Fort Randall Reach is only about 8%.

The percent of total bank line that is stabilized in the six GRs in the Fort Randall Reach ranges from about 0% to 33%. Therefore, an attempt was made to determine if there was a relationship between percent of bank line stabilized and changes in bar density. However, after a careful examination of the data, no definitive relationships could be discerned. While these results were inconclusive, they do seem to suggest that there are other controlling factors affecting the morphology of the bars and islands.

The supply of suitably sized sediment from the banks is just one factor that may influence bar morphology. Another factor that is very important is the local geometry of the reach. Although width appears to be a factor in the morphology of the bars and islands in the Fort Randall Reach the relationship was not as strong as in the other three study reaches. The mean channel width for reaches where no bars were present was about 624 m, while in the reaches with bars and islands, the mean width was about 700 m and 1,058 m, respectively. While the relationship between channel width and the presence of bars and islands was not quite as strong as in the other reaches, it still appears to be one of the dominant factors with respect to bar and island formation. Recognition of the relationship between channel width and bar morphology is important for the effective management of this system to minimize impacts to channel bars.

It should be remembered that as with any sediment transport analysis, there is considerable uncertainty in these results. Consequently, the results presented herein do not represent absolute values, but rather, should be viewed as providing a reasonable approximation of the general trends in the reach.

5.4. Gavins Point Reach

5.4.1. General Characteristics of the Gavins Point Reach.

The Gavins Point study reach extends from RM 811, just downstream of the Gavins Point Dam, to RM 753.9 near Ponca, Nebraska (Figure 5.27). This reach is regulated by the Gavins Point Dam which was under construction by the USACE from 1952 to 1957. The mean annual flow in the Gavins Point Reach is about 828 CMS. Bed material in the reach is predominately sand with occasional outcrops of gravel. The channel in this reach is relatively straight with sinuosity ranging from about 1.0 to 1.25. Many reaches exhibit a moderate to high degree of braiding with numerous bars and islands. The channel width ranges from about 185 m to 1,600 m with an average width of about 858 m. The energy slope for the Gavins Point Reach, calculated from the HEC-RAS analysis, ranges from about 0.00022 to 0.00025. The two major tributaries in the reach are the James and Vermillion Rivers, however they only supply about 5% of the total reach flow. Bank heights in this reach generally range from about 3 to 12 m with an average bank height of about 5 m. For this study the Gavins Point Reach was divided into four GRs.

The specific gauge records for the Gavins Point Reach are shown in Appendix C on the data supplement CD ROM. The gauges at Yankton, South Dakota, Gayville, South Dakota, and Maskell, Nebraska, all have period of records extending through the mid to late 1990s. Examination of the specific gauge records at these three gauges during the period from the mid 1970s to present reveals an overall degradational trend throughout the reach. According to USACE (1996), thalweg elevations for a range of discharges decreased about 2 m between 1956 and 1986. Between 1986 and 1996, about 0.5 m of lowering occurred. Thus, it appears that the Gavins Point Reach is still in an adjustment phase and has not yet attained a condition of dynamic equilibrium.

5.4.2. Relationship Between Channel Width and Bars and Islands.

The cumulative distribution relating channel width and the occurrence of bars and islands for two time periods, 1976 and 1983, is shown in Figure 5.28. Box and whisker plots for the data are shown in Figures 5.29. The analysis was also conducted with 1998 data, but the high stage at the time of the photography made it difficult to view the bars, and therefore, the results were not deemed comparable to the other dates. Although there are some minor differences, the general shape of the curves are similar for the 1976 and 1983 time periods (Figure 5.28). In general, it appears that the width for reaches with 'no bars' and 'bars' may be slightly wider in 1977 than in 1983. Figure 5.28 illustrates that reaches with no bars present are much narrower than reaches with bars or islands present. The plots in Figures 5.28 and 5.29 reveal that in 1983 the mean value of channel width for reaches with no bars was about 415 m, while the reaches with bars, and those with islands had mean channels widths of 884 m and 1,339 m, respectively. Likewise, 75% of the reaches with no bars had channel widths less than about 500 m, while less

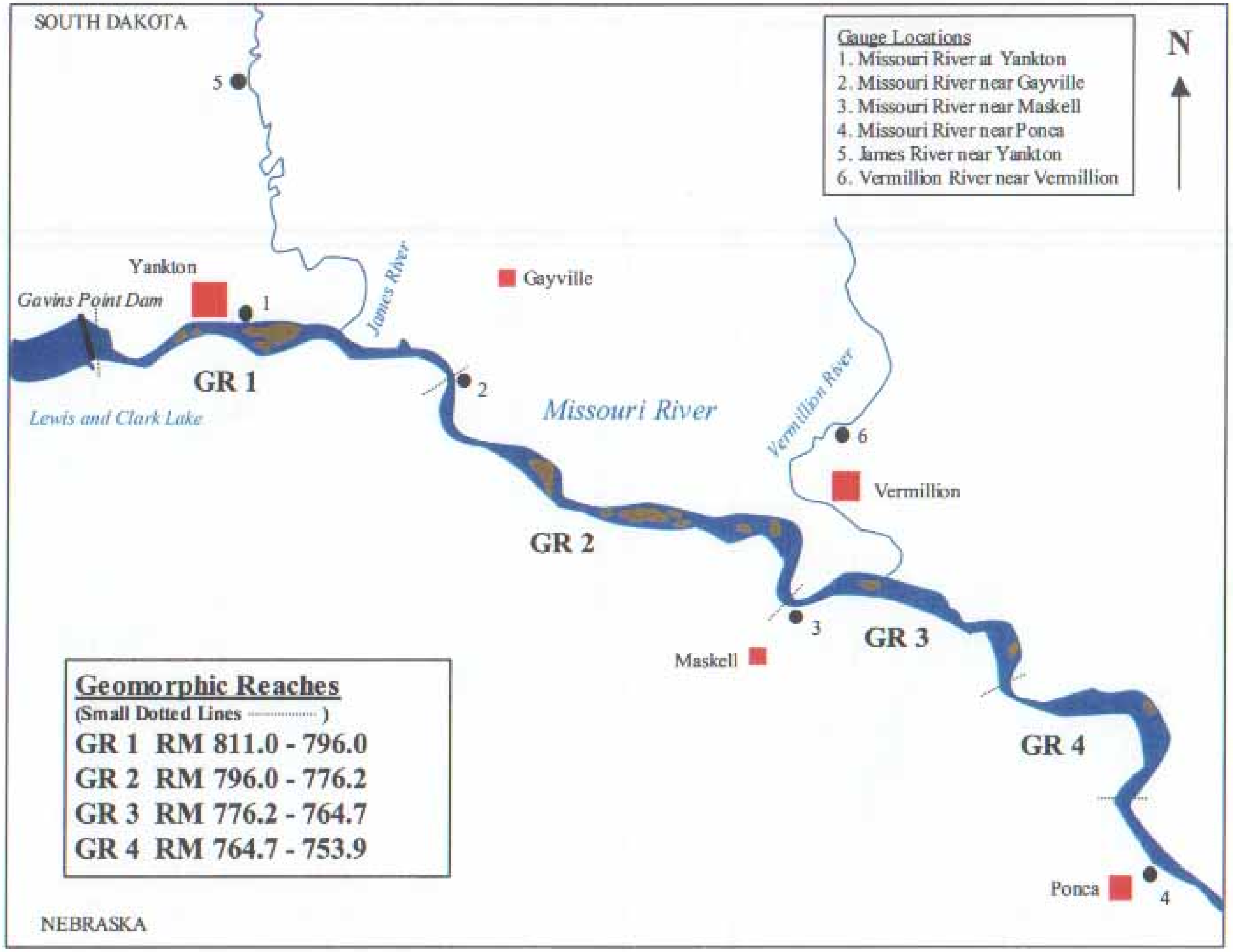
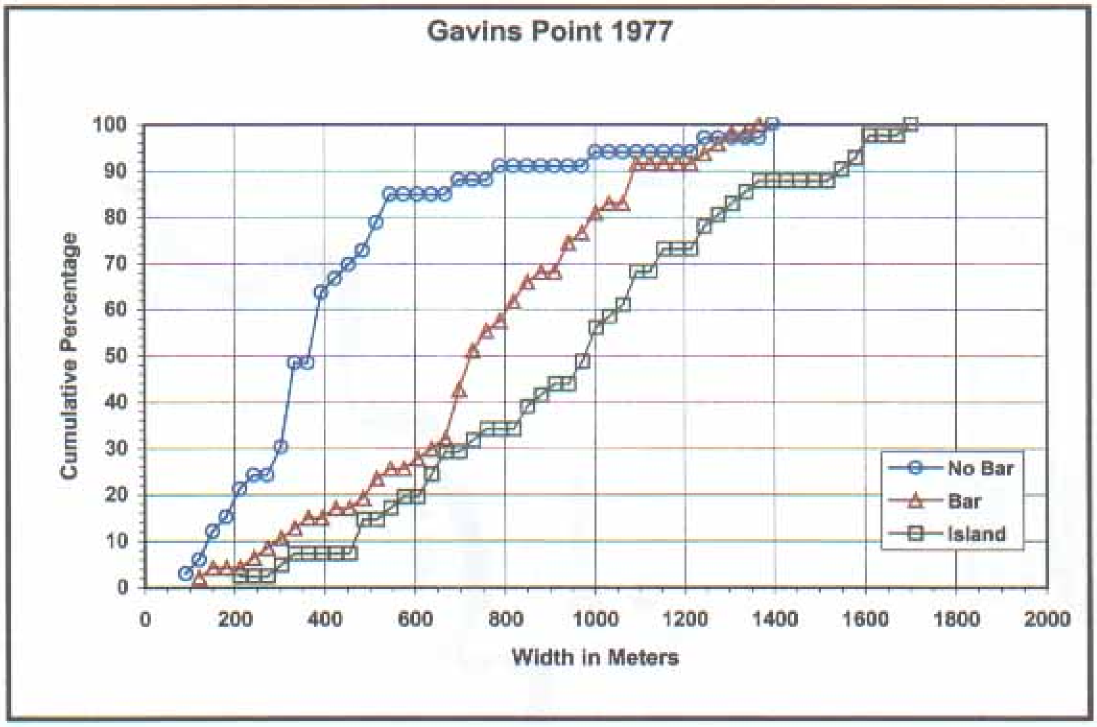


Figure 5.27 Vicinity map for the Gavins Point Reach.



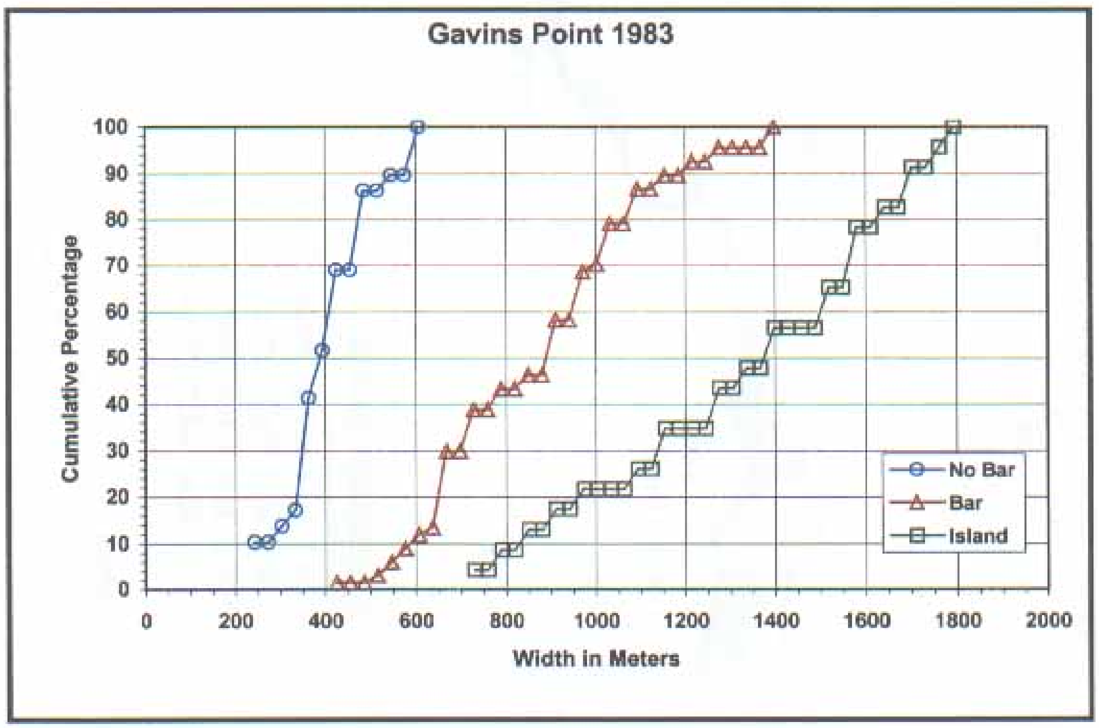


Figure 5.28 Cumulative distribution of channel width and occurrence of bars and islands for 1977 and 1983 for the Gavins Point Reach.

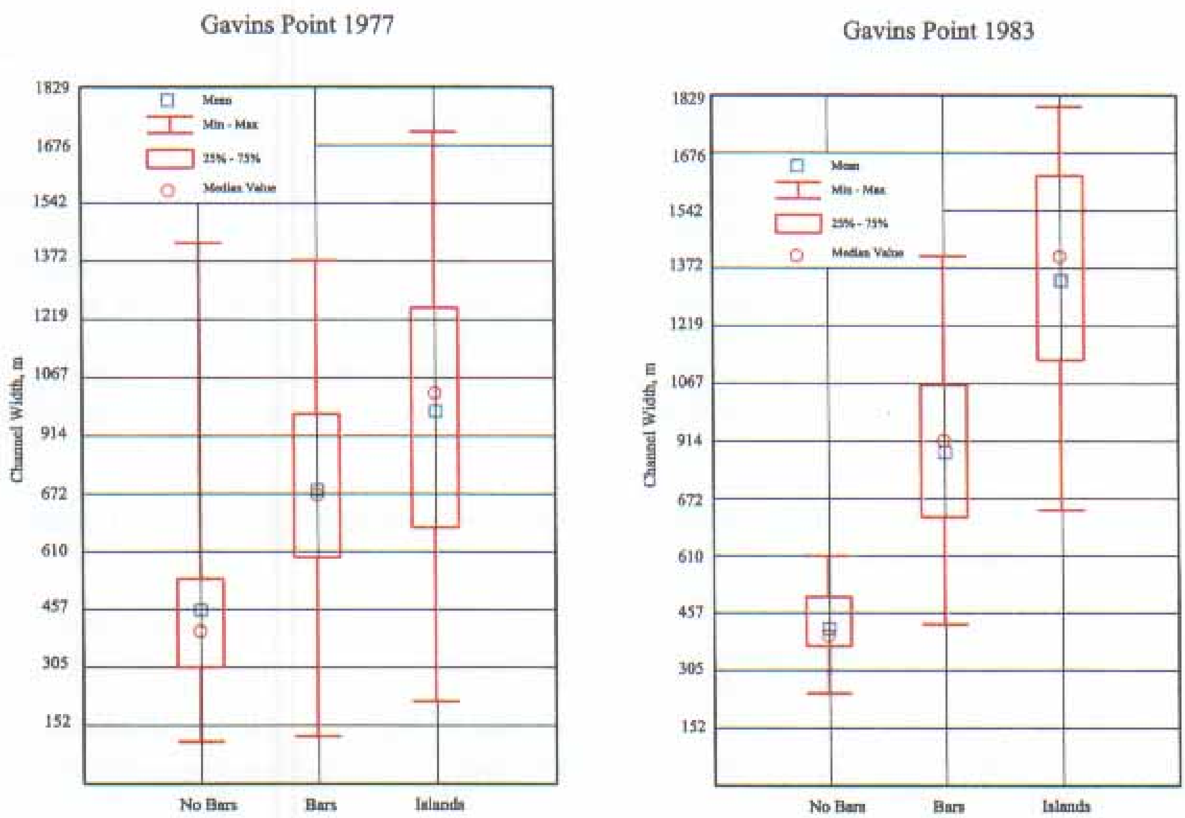


Figure 5.29 Box and whisker plots displaying the cumulative distribution of channel width and occurrence of bars and islands for 1977 and 1983, for the Gavins Point Reach.

than about 2% of the reaches with bars had a channel width less than 500 m, and no reaches with islands had widths that narrow. Thus, a channel width in the range of about 500 m appears to be a transition zone below which it is very unlikely that bars will exist. These data suggest a strong relationship between channel width and the presence of bars and islands. Thus, channel width may be a critical factor in the formation of bars and islands in the Gavins Point Reach.

5.4.3. Bar and Island Density Analysis.

The results of the bar and island density analysis for the Gavins Point Reach are shown in Table 5.19. As shown in Table 4.16, the dates of the aerial photography and the associated discharges were June 6, 1976 (906 CMS), May 5, 1994 (866 CMS), August 8, 1997 (1,826 CMS), and August 21, 1997 (1,843 CMS). Since the discharges on the days of the photography in 1997 are about twice those in the previous two periods, it might be expected that the bar and island density numbers would be somewhat less. Table 5.19 shows that the island density changes fluctuated with some reaches increasing and others decreasing, with the reach average values remaining about the same. However, the response in the bar density was quite different. As shown in Table 5.19, bar density increased in all but one reach between 1976 and 1997. These increases occurred even in reaches that were heavily stabilized (11% to 31%). However, when 1976 and 1994 are compared the bar density decreases in all but one reach. Consequently, no definitive relationship between stabilization and bar and island density could be established for the Gavins Point Reach.

Table 5.19 Island and sandbar density and percent of bank line stabilized for Gavins Point Reach.

	Gavins Point Reach, Island and Sandbar Density						Aerial Mosaic August 10, 1985		
	1960 RM		Reach Length (km)	Density (ha/km)			Percent of Reach Revetted		
	Upstream	Downstream		As of 1976	As of 1994	As of 1997	Left	Right	Total
Islands	811	801	16.1	61.1	59.3	19.8	0.0	0.0	0.0
	801	791	16.1	4.1	4.2	50.7	22.9	18.6	20.7
	791	781	16.1	36.7	36.0	53.1	26.5	29.5	28.0
	781	771	16.1	19.3	15.4	15.5	22.2	0.8	11.5
	771	766	8.0	23.1	14.9	47.4	37.1	25.0	31.1
	766	751	24.1	2.9	6.1	0.1	20.0	16.9	18.4
	Entire Reach Average		96.5	25.8	24.4	27.2	-	-	-
Sandbar	811	801	16.1	7.3	3.3	8.1	0.0	0.0	0.0
	801	791	16.1	16.3	2.2	30.1	22.9	18.6	20.7
	791	781	16.1	13.5	4.1	41.0	26.5	29.5	28.0
	781	771	16.1	10.6	0.1	51.0	22.2	0.8	11.5
	771	766	8.0	22.5	4.8	41.9	37.1	25.0	31.1
	766	751	24.1	31.6	53.5	22.1	20.0	16.9	18.4
	Entire Reach Average		96.5	16.5	11.5	30.7	-	-	-

5.4.4. Sediment Gradation Analysis.

Figure 5.30 shows the reach average gradation curves in the Gavins Point Reach for the habitat bars, non-habitat bars, tributaries, banks, and channel bed. The D_{10}, D_{50}, and D_{90} values for these features are shown in Table 5.20. The individual gradation curves for the banks, habitat bars, non-habitat bars, and tributaries are shown in Figures 5.31, 5.32, 5.33, and 5.34, respectively.

Table 5.21 presents the average bank gradation curves that were developed to represent each geomorphic reach in the Gavins Point Reach. These data are also shown graphically in Figure 5.31. An overall average bank gradation curve for the entire Gavins Point Reach is also provided in Figure 5.31. As indicated in Table 5.21, two gradation curves were used to represent the Gavins Point Reach. One curve was used for GR 1, and the second curve was used to represent GRs 2, 3, and 4. The gradation curves for the habitat bars in the Gavins Point Reach are shown in Figure 5.32. As shown in Figure 5.32 there are essentially no fines (less than 0.063 mm) found in the habitat bars.

Figure 5.30 indicates that the non-habitat bars are slightly finer than the habitat bars, and that the banks are finer than the bars. Figure 5.30 also shows that the bed is coarser than the bars and banks. Examination of the samples taken near the mouth of the James River contains some fines as well as considerable amounts of coarse material.

As indicated in Figure 5.30 there are essentially no fines (less than 0.063 mm) present in the bed. The average bed D_{10} value for the entire reach is about 0.23 mm. As indicated in Table 5.20, the average D_{10} for the habitat bars is about 0.2 mm. This suggests for the Gavins Point Reach, that material finer than about 0.2 mm is not in appreciable quantities in the bed and habitat bars. Therefore, sediment load composed of material greater than 0.2 mm is considered bed material load while material finer than this behaves as wash load.

As shown in Table 5.21, the percent of the bank material finer than 0.063 mm ranged from about 14% to 25% with an average of about 19%. Thus, about 19% of the material eroded from the banks are fines (silts and clays) which are essentially nonexistent in the bed and habitat bars. The percent of the bank material coarser than 0.2 mm ranged from about 44% to50% with an average of about 47%. Thus, for the Gavins Point Reach, about 47% of the material eroded from the banks is of the same size as the material found in appreciable quantities in the bed or habitat bars, and thus contributes to the bed material load.

5.4.5. Bank Erosion Analysis.

A summary of the total bank erosion results for the Gavins Point Reach is shown in Table 5.22. As indicated in Table 5.22, annual bank erosion rates per kilometer range from about 15,000 m^3/yr/km in GR 1 to about 43,000 m^3/yr/km in GR 3. The overall reach average rate is about 28,000 m^3/yr/km. Thus, the Gavins Point Reach has the highest bank erosion rates per kilometer of the four study reaches.

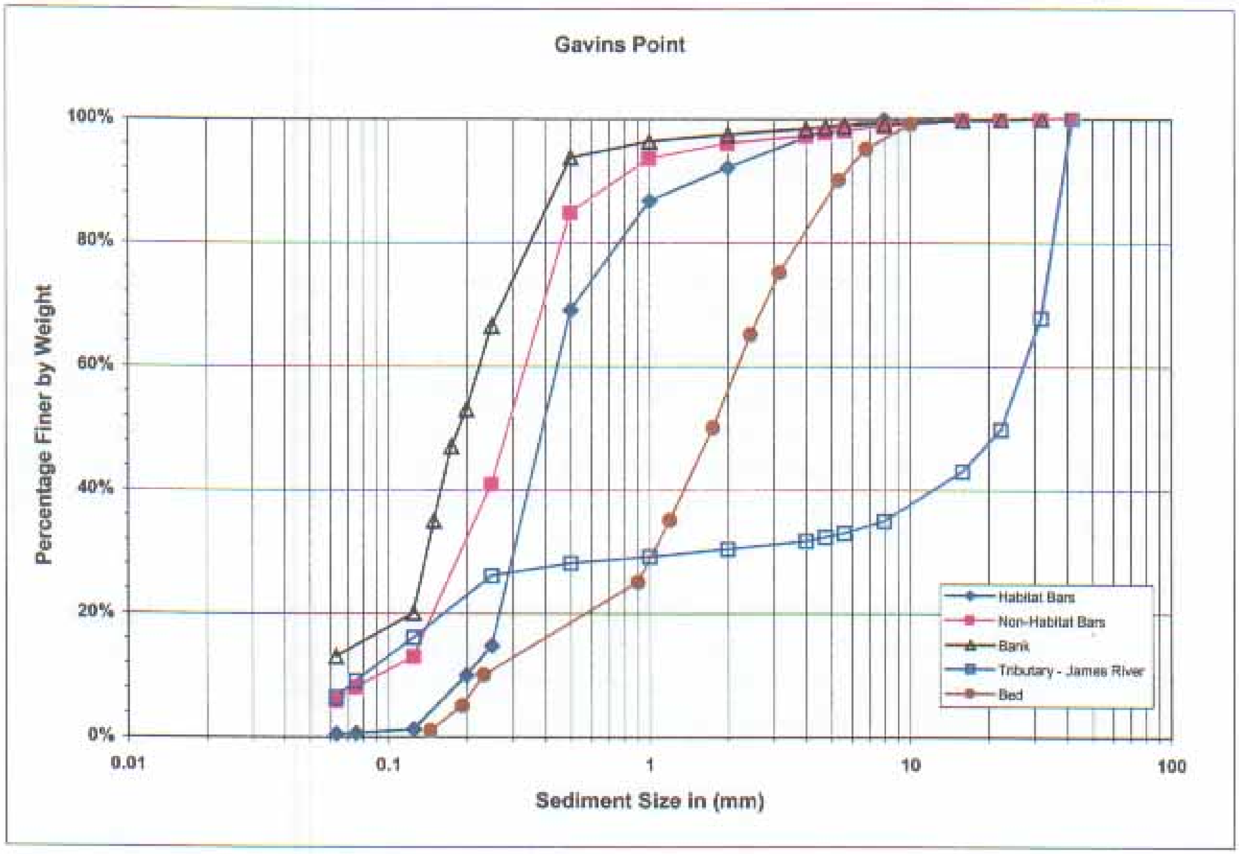


Figure 5.30 **Reach average gradation curves for the habitat bars, non-habitat bars, tributaries, banks, and channel bed for the Gavins Point Reach.**

Table 5.20 **Gavins Point Reach average D_{10}, D_{50} and D_{90} values for habitat bars, non-habitat bars, tributaries, banks, and channel bed.**

Percent	Reach Average Habitat Bar (mm)	Reach Average Non-habitat Bar (mm)	Reach Average Tributary WPT 13 James River (mm)	Reach Average Banks (mm)	Reach Average Bed (mm)
D_{10}	0.20	0.09	0.08	-	0.23
D_{50}	0.39	0.29	22.55	0.19	1.75
D_{90}	1.55	0.76	38.61	0.45	5.35

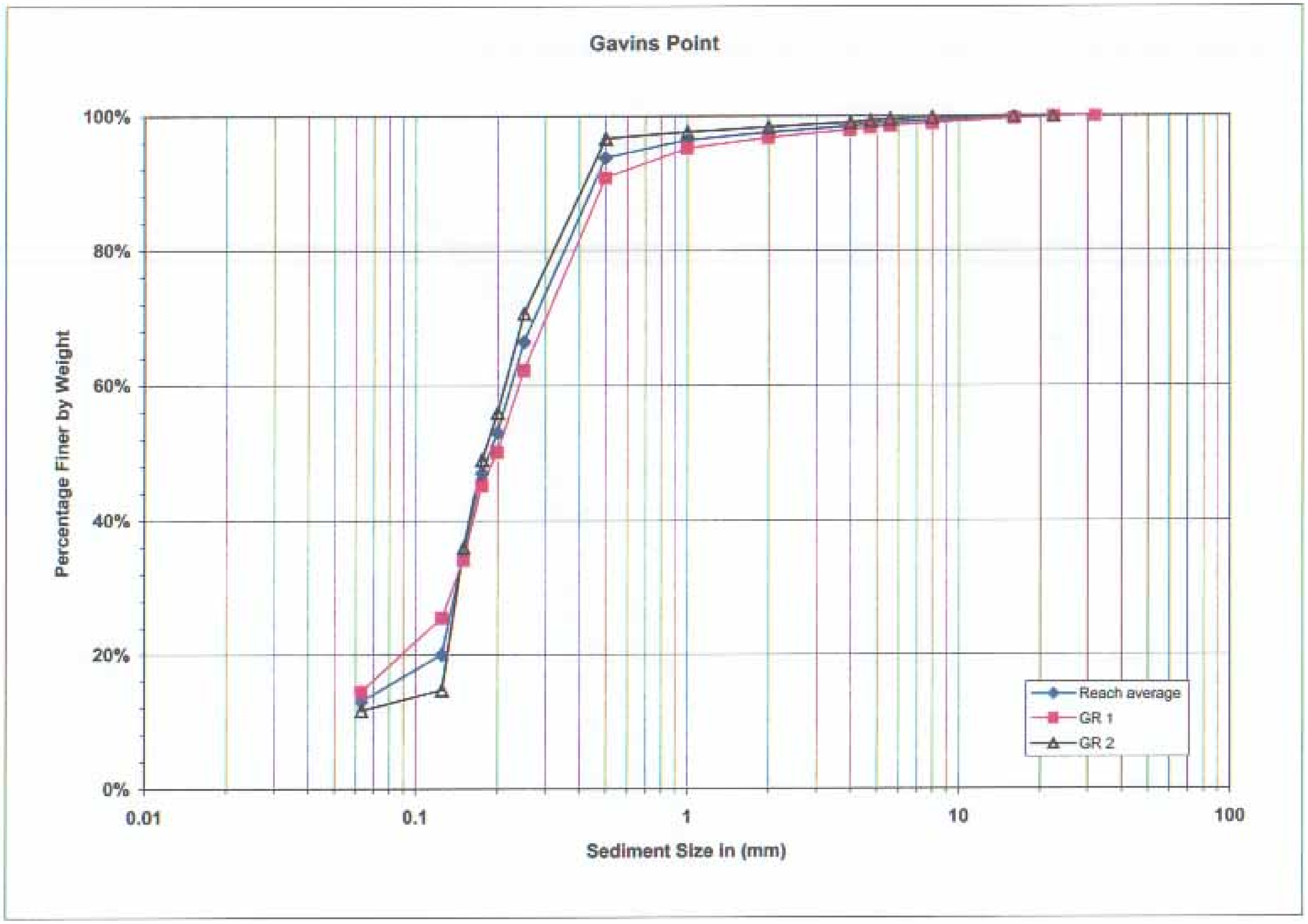


Figure 5.31 Average bank gradation curves for the individual geomorphic reaches and the reach average for the Gavins Point Reach.

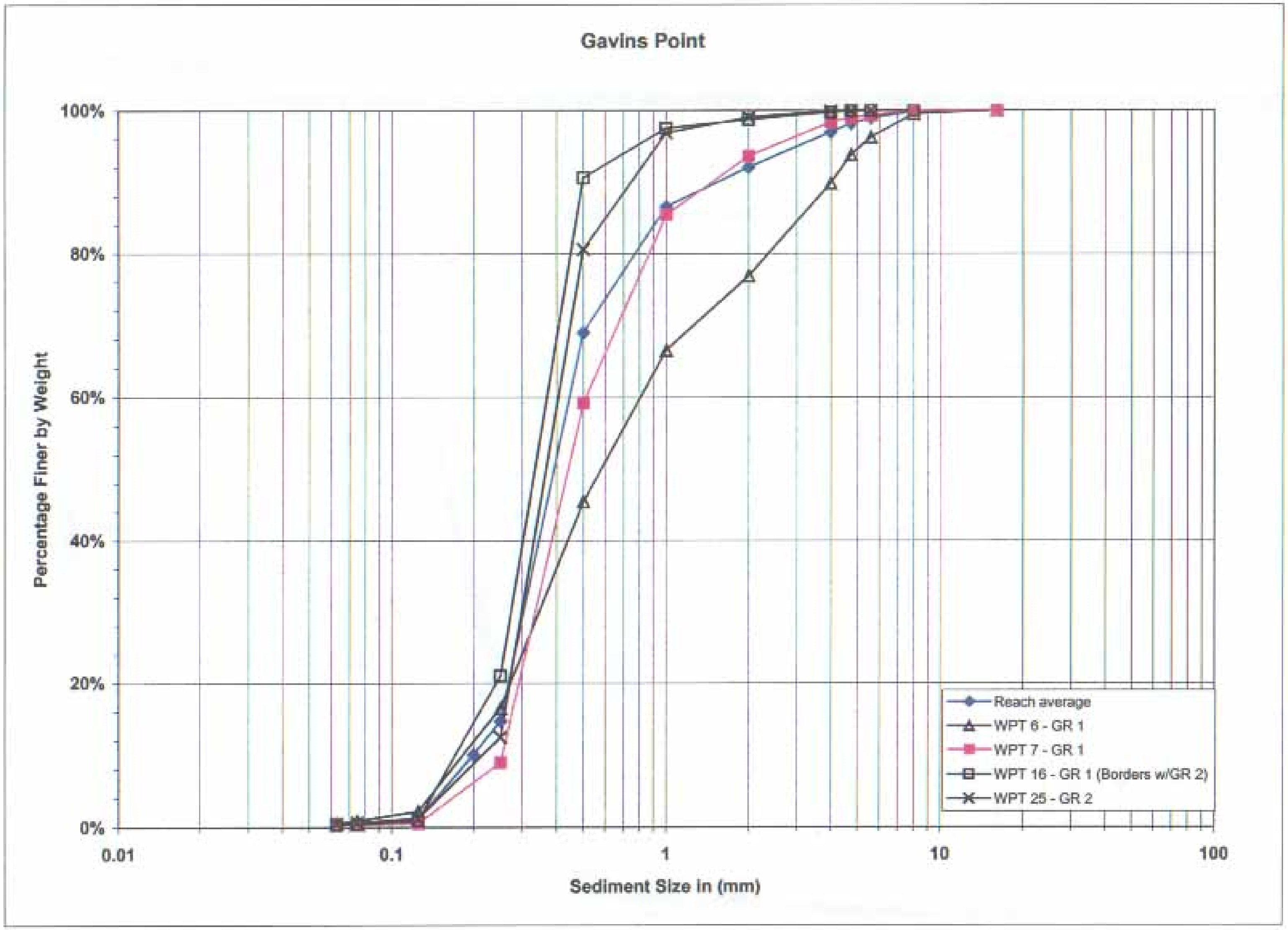


Figure 5.32 Gradation curves for each habitat bar and the reach average for the Gavins Point Reach.

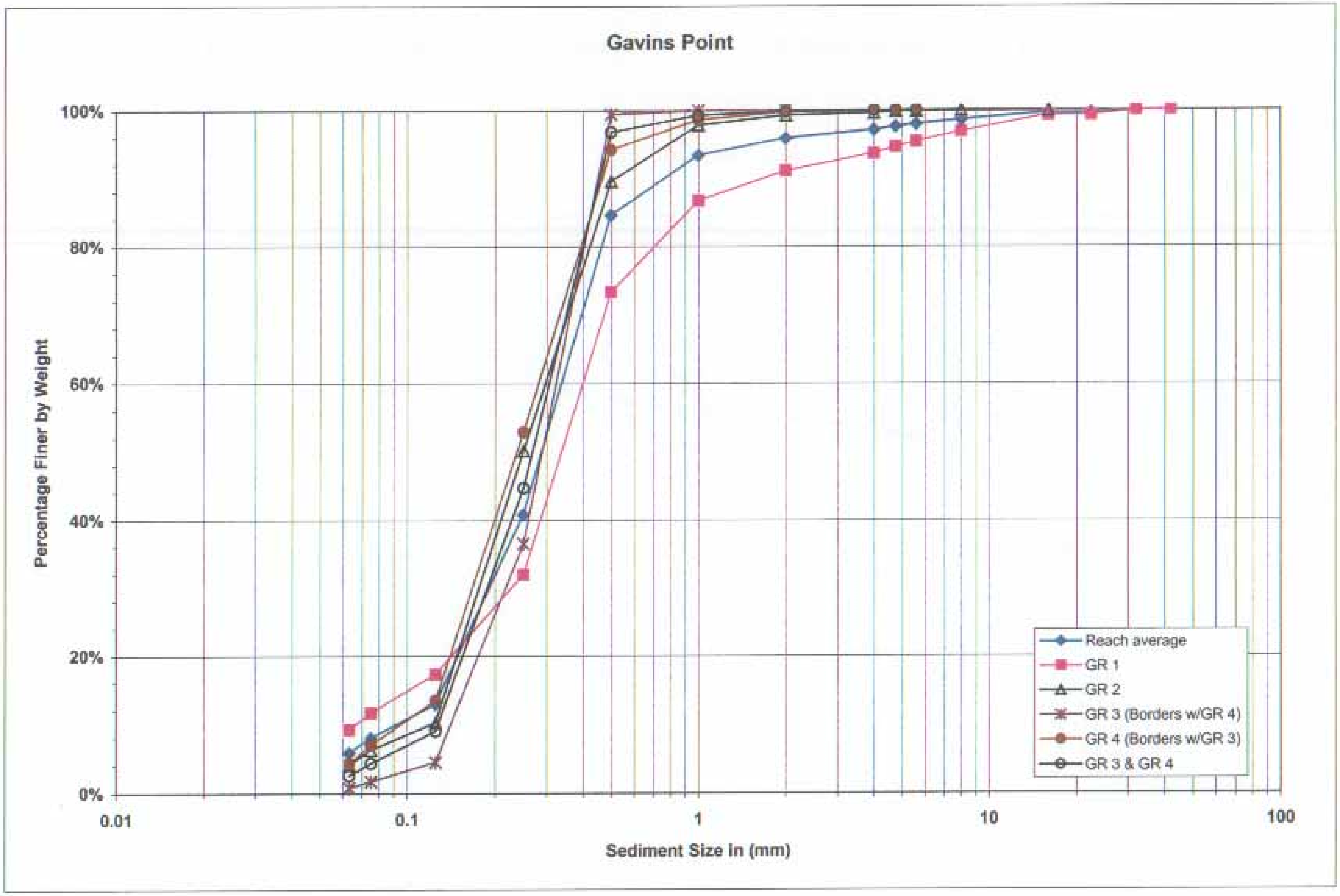


Figure 5.33 Average non-habitat bar gradation curves for individual geomorphic reaches and the reach average for the Gavins Point Reach.

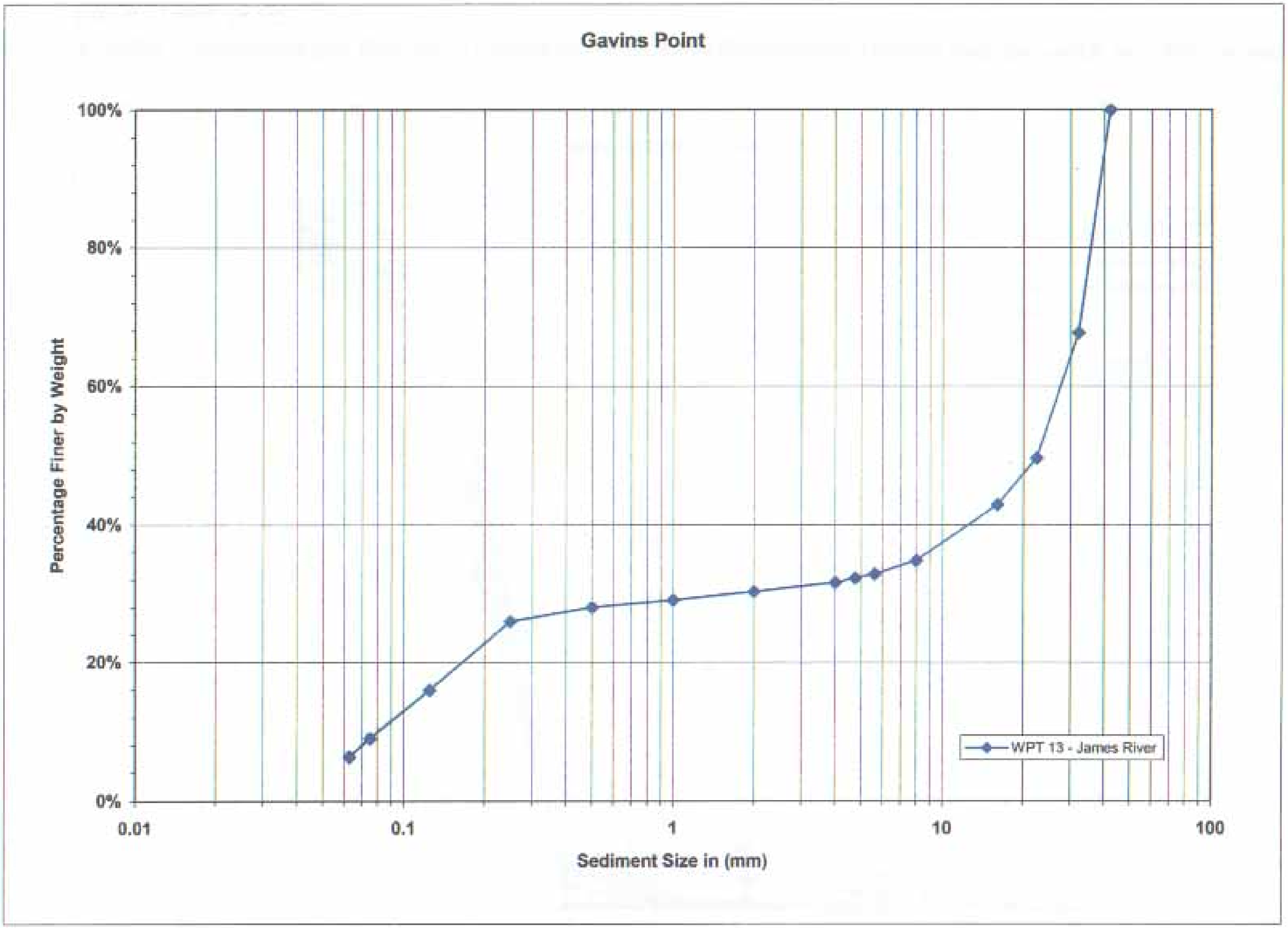


Figure 5.34 Gradation curve for the James River tributary in the Gavins Point Reach.

Table 5.21 Average bank gradation curves for each geomorphic reach in the Gavins Point Reach.

Geomorphic Reach (RM)	WPT	Grain Size (mm) Percent Finer by Weight																	
		0.063	0.125	0.14	0.15	0.16	0.175	0.2	0.25	0.5	1	2	4	4.75	5.6	8	16	22.4	32
GR 1 (811.0-796.0)	2,3,4,5, 8,9,10,1 2,17	14.38%	25.40%	30.00%	34.00%	36.00%	45.00%	50.00%	62.15%	90.83%	95.14%	96.71%	97.86%	98.20%	98.46%	98.86%	99.58%	99.89%	100.00%
GRs 2, 3 & 4 (794.16-752.0)	19,20,22 ,23, 24, 26,27, 29,30	11.61%	14.69%	29.00%	36.00%	38.00%	49.00%	56.00%	70.68%	96.68%	97.63%	98.34%	99.01%	99.28%	99.49%	99.74%	99.97%	100.00%	

Table 5.22 Gavins Point bank erosion from 1977 to 1998.

Geomorphic Reach (RM)	Left Bank Erosion (m^3)	Right Bank Erosion (m^3)	Total Volume (m^3)	Annual Volume (m^3/yr)	Distance River (km)	Annual Volume/km (m^3/yr/km)
GR 1 (811-796)	2,925,063	5,145,819	8,070,882	366,858	24.1	15,200
GR 2 (795-776)	7,393,556	9,599,230	16,992,785	772,399	30.6	25,266
GR 3 (775-764)	5,706,287	11,028,291	16,734,578	760,663	17.7	42,978
GR 4 (763-752)	3,878,527	9,371,188	13,249,715	602,260	17.7	34,028
Total	19,903,433	35,144,528	55,047,961	2,502,180	90.1	27,770

Note: Total in column 7 is the total annual volume ÷ total river distance

5.4.6. Sediment Budget.

As discussed in Section 5.4.4, the bed material load in the Gavins Point Reach is comprised of material greater than about 0.2 mm. Therefore, the bank erosion volumes used in the Gavins Point sediment budget reflect the contribution of bank material greater than 0.2 mm. The sediment budget for the Gavins Point Reach is shown in Table 5.23. As shown in Table 5.23, there is a general increase in bed material transport throughout the entire Gavins Point Reach. This indicates that the entire Gavins Point Reach exhibits a degradational trend, which is consistent with the trends discussed in Section 5.4.1

Table 5.23 Gavins Point sediment budget with >0.20 mm bed material size.

Geomorphic Reaches (RM)	Erosion		Deposition		Net Sediment Transport from Erosion & Deposition (m^3/yr)	Upstream Sediment Supply (m^3/yr)	Sediment Transport Budget (m^3/yr)
	Bank (1977-1998) (m^3/yr)	Bed (1974-1986) (m^3/yr)	Bank (1974-1986) (m^3/yr)	Bed (1974-1986) (m^3/yr)			
GR 1 (811- 796)	-192,290	-343,540	61,978	10,835	-463,017		-463,017
GR 2 (795-776.2)	-356,272	-569,242	95,554	95,341	-734,619	-463,017	-1,197,636
GR 3 (775-764.7)	-639,185	-361,611	61,200	54,843	-884,753	-1,197,636	-2,082,388
GR 4 (763-752)	-411,151	-589,490	164,340	105,843	-730,458	-2,082,388	-2,812,846
Total (811.0-752)	-1,598,898	-1,863,883	383,072	266,863	-2,812,846		

Table 5.24 shows the reduction in the supply of bed material sized sediment (greater than 0.2 mm) from bank erosion that would result from stabilization of 10% to 100% of the eroding areas for each of the GRs. As illustrated in Table 5.24, the impacts of bank stabilization vary from reach to reach. In GR 1, the banks contribute about 45% of the total bed material load in

that reach. Therefore, if all bank erosion was eliminated by bank stabilization, there would be a reduction in the supply of bed material sized sediment in this reach of about 41%. As a consequence, the river would acquire this additional load from scouring the bed, bars, and/or remaining unprotected banks in the reach. In the other reaches, the bank contributions range from about 15% to 31%. Therefore, the sediment transport impacts associated with bank stabilization in these reaches should be less. Table 5.24 also allows for the determination of the impacts associated with only stabilizing some of the eroding areas. For instance, in GR1, if 20 percent of the eroding areas were stabilized, there would be about an 8% reduction in the supply of bed material sized sediment to the reach. However, if 50% of the eroding areas were stabilized, the reduction would be about 21%.

Table 5.24 Bank stabilization impact on the Gavins Point Reach.

Gavins Point budget with >0.20 mm bed material size.

	Geomorphic Reaches				
Revetment Percentage	**Reduction of Bank Contribution GR 1 RM 811-RM 796**	**Reduction of Bank Contribution GR 2 RM 796-RM 776.2**	**Reduction of Bank Contribution GR 3 RM 776.2-RM 764.2**	**Reduction of Bank Contribution GR 4 RM 764.7-RM 753.9**	**Reach Average Reduction of Bank Contribution RM 811 – RM 753.9**
10	4%	3%	3%	1%	2%
20	8%	6%	6%	3%	5%
30	12%	9%	9%	4%	7%
40	17%	12%	12%	6%	10%
50	21%	15%	15%	7%	12%
60	25%	18%	18%	9%	15%
70	29%	21%	21%	10%	17%
80	33%	24%	25%	12%	20%
90	37%	27%	28%	13%	22%
100	42%	30%	31%	15%	24%

Table 5.24 also shows the reach average values for the entire Gavins Point Reach. Considering the entire Gavins Point Reach, the banks supply about 24% of the bed material load. Thus, on a gross reach level, the effects of stabilizing all eroding areas would reduce the supply of bed material by about 24%.

5.4.7. Discussion of Results.

When the banks in the Gavins Point Reach are compared to the bars, it is found that the bars are generally somewhat coarser than the banks. Non-habitat bars were found to be slightly finer than the habitat bars. The habitat bars in this reach are composed almost entirely out of sand sized material with the average D_{10} being about 0.2 mm. The channel bed is slightly coarser than the habitat bars with an average D_{10} of about 0.23 mm. A grain size of 0.2 mm was selected to represent the lower size limit of material found in appreciable quantities in the bed and habitat bars for this reach. The percent of bank material coarser than 0.2 averaged about 47%. This suggests that for the Gavins Point Reach, about 47% of the material eroded from the banks is of a size found in appreciable quantities in the bed or habitat bars, and therefore may contribute to the bed material load.

The sediment budget for the Gavins Point Reach revealed that the entire reach is in a degradational trend, and has not yet attained an equilibrium condition. Gavins Point has the largest amount of bank erosion of any of the four study reaches, with a total annual volume of material eroded from the channel banks of about 2,502,000 m^3/yr, or about 28,000 m^3/yr/km. While this is a large number, it must be remembered that only about 47% of this material contributes to the bed material load in the reach. Therefore, the overall contribution from bank erosion to the bed material load in the Garrison Reach is only about 24%. However, at the reach scale, the material supplied from bank erosion in GR 1 and GR 2 represents about 42% and 30% of the total bed material load, respectively. Conversely, bank erosion in GR 3 contributes about 31% of the total bed material load.

The Gavins Point Reach has a considerable amount of bank stabilization in it, with the percent of total bank line that is stabilized ranging from about 0% to 31%, and a reach average of about 17%. Therefore, an attempt was made to determine if there was a relationship between percent of bank line stabilized and changes in bar density. However, after a careful examination of the data, no definitive relationships could be discerned. Heavily stabilized reaches exhibited both increases and decreases in bar and island density. While these results were inconclusive, they do seem to suggest that there are other controlling factors affecting the morphology of the bars and islands.

The supply of suitably sized sediment from the banks is just one factor that may influence bar morphology. Another factor that is very important is the local geometry of the reach. This analysis revealed a strong relationship between channel width and the presence or absence of bars. Reaches with bars and islands present were much wider than reaches without bars. The mean channel width for reaches where no bars were present was about 415 m, while in the reaches with bars and islands, the mean width was about 884 m and 1,334 m, respectively. A total of 75% of the reaches with no bars present had a channel width less than 500 m, while less than 2% of reaches with bars, and no reaches with islands had channel widths less than 500 m. Therefore, a channel width in the range of about 500 m appears to be a transition zone below which it is very unlikely that bars will exist. Thus, it appears that channel width is a major factor affecting the morphology of the bars and islands in the Gavins Point Reach. Recognition of the relationship between channel width and bar morphology is important for the effective management of this system to minimize impacts to channel bars.

It should be remembered that as with any sediment transport analysis, there is considerable uncertainty in these results. Consequently, the results presented herein do not represent absolute values, but rather, should be viewed as providing a reasonable approximation of the general trends in the reach.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

Presented in Table 6.1 is a summary of some of the basic characteristics for each of the four study reaches. As indicated in Table 6.1, Garrison and Gavins Point Reaches have the largest percentage of revetments with 21% and 17% of the bankline being revetted, while Fort Randall Reach has about 12% and Fort Peck Reach essentially has none. The lowest energy slopes occur in the Fort Randall Reach with slopes ranging from about 0.00006 to 0.00012. The Gavins Point Reach has the highest energy slopes, with slopes ranging from about 0.00022 to 0.00025. The Gavins Point Reach also has the largest mean annual discharge at about 828 CMS, while Fort Peck has the smallest with about 345 CMS. The high energy slope and discharges may help explain why the Gavins Point Reach also has an average annual bed material load that is more than twice the other three study reaches. Fort Randall has the lowest average bed material load at only about 265,000 m^3/yr. A partial explanation for this low value may be due to the low energy slopes and large channel widths in this reach. As well as the highest bed material load, Gavins Point also has the largest amount of bank erosion of any of the four study reaches. As shown in Table 6.1, the reach-average percent of bank material that is of a size found in appreciable quantities in the bed and habitat bars ranges from only about 21% in the Fort Randall Reach to 60% in the Garrison Reach. Bank erosion in the Gavins Point Reach supplies about 13,000 m^3/yr/km of bed material sized sediment. This value is an order of magnitude greater than the other three reaches. In the Gavins Point Reach, the percent bank contribution to the bed material load is about 24%, which is the highest of the four study reaches. The percentages in the Fort Peck and Garrison Reaches are 17% and 13%, respectively, while the banks in the Fort Randall Reach contribute the smallest percentage to the bed material load at about 8%.

One of the primary aims of this study was to determine the potential impacts of future bank stabilization on the habitat bars in the four study reaches. The results of this study provide considerable new insight into the potential impacts of bank stabilization on the reduction of the supply of bed material sized sediment from the banks. However, the precise impacts on the channel morphology and, in particular, the habitat bars, is less clear. Consequently, an attempt was made to establish a relationship between percent bank stabilization and impacts to habitat bars. However, no reliable relationship could be found. Rather, the investigation revealed that there are multiple factors that affect bar morphology. The three primary factors necessary for the formation and persistence of bars are a supply of suitably sized sediment, a local channel geometry and a stability status that allows and promotes bar existence. In a system such as the Missouri River, where there is an abundant supply of material, the local geometry is probably the dominant factor with respect to bar morphology. As a consequence, when considering the potential impacts of a proposed bank stabilization scheme, the investigator can not just focus on one factor, but rather must consider a number of factors. Each bank stabilization project should

Table 6.1 Summary of basic characteristics for each of the four study reaches.

Study Reach	Percent Revetment	Average Channel Width (m)	Energy Slope	Mean Annual Discharge (CMS)	Annual Bed Material Load (m^3/yr)	Annual Bank Erosion (1000 m^3/yr)	% Bank Material >Bed Material Size	Supply of Bed Material Sized Sediment from Banks (m^3/yr/km)	% Bank Contribution to Bed Material Load
Fort Peck	0	310	0.0003-0.0005	345	550	1,600	48%	2,900	17%
Garrison	**21**	615	0.0001-0.00013	655	610	825	**60%**	4,400	13%
Fort Randall	12	826	0.00006-0.00012	801	265	720	21%	3,000	8%
Gavins Point	17	**858**	**0.00022-0.00025**	**828**	**1,600**	**2,500**	47%	**13,000**	**24%**

* numbers in Bold represent largest of the four reaches

be evaluated on a case by case basis in an engineering-geomorphic investigation that identifies and quantifies the impacts of channel width, reduction in sediment supply, and existing stability of the reach. A discussion of these factors follows.

6.1 Channel Width

Local channel geometry and, in particular, channel width, is one of the dominant factors that affects bar and island morphology. The results of this study revealed that there is a strong relationship between width and the presence or absence of bars and islands. Threshold values for channel width were established, below which the persistence of bars was unlikely. The threshold values for the Fort Peck, Garrison, and Gavins Point Reaches are about 250 m, 630 m, and 500 m, respectively. Because of the highly braided character of the Fort Randall Reach, no threshold value could be established. It must be remembered that these threshold values are not absolute, but are presented as a general guide. It is recommended that a range of values be identified rather than focusing too precisely on a single threshold value. For instance, on the Fort Peck Reach the threshold range might extend from 225 m to 285 m. Depending on the local situation, the engineer might select a slightly smaller or larger threshold range to reflect the desire for more or less conservatism in the approach. After the threshold range is selected, the width of the proposed stabilization site should be measured. If the width is significantly less than the threshold range, then bars are unlikely to occur regardless of whether bank stabilization is implemented or not. If the width is significantly greater than the threshold range, then the impacts of typical bank stabilization measures that do not significantly reduce the channel width may not be significant. However, if the proposed site has a width that is near the threshold range, then the reach might be considered very sensitive to relatively small width changes with respect to the formation or persistence of bars. Therefore, any stabilization measures that would reduce the channel width in these areas should be considered carefully. This might be particularly important if the stabilization measures physically reduced the channel width, as would be the case with transverse structures (dikes). Another situation that could be significant would be if both banks of the river were stabilized or if the bank opposite the proposed stabilization measures was composed of naturally erosion resistant material, since this would essentially be locking the channel width into the threshold range. On the other hand, if only one bank was to be stabilized with traditional revetments or short hard points, and the opposite bank was free to adjust, through new or continued retreat, then the width impacts on bar formation or persistence would be much less.

6.2 Reduction of Bed Material Sized Sediment from the Banks

The second factor affecting bar morphology is the supply of sediment of the appropriate size to build and maintain bars. It was noted above that in a very wide reach (much wider than the threshold range), the impacts of bank stabilization might not be too significant. However, this ignores the second major factor that affects bar morphology – the sediment supply. Therefore, the impacts of the proposed bank stabilization on the contribution from the banks to the bed material load should be considered. For instance, if the proposed bank stabilization project is shown to reduce the contribution of bed material sized sediment by 30% then the potential impacts on bar morphology would potentially be much greater than if the contribution of sediment was only reduced by about 10%. As a result of a reduced supply of bed material sized sediment from the banks, the channel will attempt to acquire additional sediment from the bed, bars, islands, or remaining unprotected banks. However, determining exactly where this sediment will be obtained from is beyond the scope of this study, and would require a much more detailed, site specific analysis of the reach.

Another way to assess the impacts of bank stabilization on bar morphology is to evaluate the existing stabilized reaches for changes in bar and island density resulting from the stabilization measures. After close examination of the data, no definitive trends or relationships between bar density and percent bank stabilization could be identified. The results showed that there were both increases and decreases in bar density regardless of whether bank stabilization had been implemented. These results seem to indicate that bank stabilization and the resulting reduction in sediment supply have a very limited impact on bar density. However, it should be noted that even in the most heavily stabilized reaches, the percent of stabilized bank line was only about 35%. Therefore, there were no data to address potential impacts where more than 35% of the bank lines were stabilized.

Tables are provided in each study reach to predict the potential reduction in supply of bed material sized sediment from the banks as a result of stabilizing 10% to 100% of the eroding areas. These tables help to put into perspective the overall contribution of the banks to the bed material transport in each reach. However, it must be remembered that these results reflect the potential response at the reach scale, and that local adjustments are not addressed by this analysis. In order to address the local dynamics, a more detailed analysis would be necessary, possibly requiring the application of a two-dimensional sediment transport model.

6.3 Overall Stability of the Reach

The third major factor that should be considered when evaluating a potential bank stabilization project is the overall stability of the reach. This is because the response to a reduction in sediment supply from the banks may be different in an aggradational reach than in a degradational reach. If bed material supply is reduced in an aggradational reach, the response may simply be a decrease or elimination of aggradation in the reach depending upon the magnitude of the reduction. If the reach is already degradational, then the reduction in supply of sediment would simply exacerbate the degradational trends. For example, in GR 6 in the Fort Randall Reach, about 386,000 m^3/yr is supplied to the reach from upstream while only about 370,000 m^3/yr is transported out (Table 5.17). Thus, this is an aggradational reach with an annual depostional rate of about 16,000 m^3/yr. The bank supply in this reach is about 49,000 m^3/yr. Therefore, if 10% of the banks were stabilized, the reduction in supply from the banks would be about 4,900 m^3/yr, which is still less than the depostional rate. Therefore, this alternative might be considered to have a low potential for causing increased scour. However, if 100% of the banks were stabilized, then there would be a deficit of about 33,000 m^3/yr that would have to be acquired from the scour of the bed, bars, or remaining unprotected banks. Thus, this alternative would have to be examined more closely as it could potentially change the morphological evolutionary trend from aggradational to degradational.

6.4 Integration of Results

As discussed above, each potential bank stabilization project should be evaluated with respect to channel width, reduction in sediment supply from the banks, and the existing stability of the reach. It should be remembered that due to the data gaps and stochastic nature of alluvial processes associated with a complex river system such as the Missouri River, a considerable amount of uncertainty is included in any study results. Therefore, the integration process must be accomplished by river engineers whose knowledge of the system will allow them to temper the results with their experiences in order to develop rational solutions.

CHAPTER 7

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APPENDIX A: GRAIN SIZE DATA FOR MISSOURI RIVER

The grain size data file is in Appendix_A on the data supplement CD ROM that accompanies this report. These data were introduced in Section 4.2. Organization of Appendix_A is as follows:

File Name	Contents
A1_Missouri_GS_ Distribution.xls	Worksheet 1 (A1.1 Master GSD Sheet) includes sieve analysis results for all of the samples. A catalog of waypoints for all the reaches, including WPT number, approximate RMs, and location, are presented as follows: Worksheet 2 (A1.2 Fort Peck WPTs) Worksheet 3 (A1.3 Garrison WPTs) Worksheet 4 (A1.4 Fort Randall WPTs) Worksheet 5 (A1.5 Gavins Point WPTs)

APPENDIX B: GEOLOGY DATA FOR ALL FOUR REACHES

These summaries are included in Appendix_B on the data supplement CD ROM that accompanies this report. The information about bedrock types adjacent to the river was included in the geomorphic characterization and classification of the reaches as well. These data were introduced in Section 4.3. Organization of Appendix_B is as follows:

File Name	Contents
B1_Garrison.doc	"Geology of the Missouri River, Garrison Reach, Southwest North Dakota" which includes information about bedrock types adjacent to the river in this geomorphic characterization and classification of the reaches
B2_Fort_Randall-Gavins_Point.doc	"Formations Adjacent to the Missouri River, Fort Randall Reach and Gavins Point Reach, Nebraska, and Southeastern South Dakota" which includes information about bedrock types adjacent to the river in this geomorphic characterization and classification of the reaches
B2_Figures_Fort_Randall-Gavins_Point.ppt	Figures B2.1 through B2.4 for "Formations Adjacent to the Missouri River, Fort Randall Reach and Gavins Point Reach, Nebraska, and Southeastern South Dakota"

APPENDIX C: SPECIFIC GAUGE DATA FOR ALL FOUR REACHES

The actual specific gage records are shown in Appendix_C on the data supplement CD ROM that accompanies this report. These data were introduced in Section 4.4. Organization of Appendix_C is as follows:

Directory	File Name	Contents
Fort_Peck	Figure_C1.xls	Fort Peck Reach: Specific Gauge Record for Gauge No. 1 (2.61 mi downstream of dam), MT - RM 1768.9
	Figure_C2.xls	Fort Peck Reach: Specific Gauge Record for 7 Mile Gauge (Missouri River below Fort Peck Dam), MT - RM 1763.5
	Figure_C3.xls	Fort Peck Reach: Specific Gauge Record for the Milk River at Nashua, MT - RM 1761.6
	Figure_C4.xls	Fort Peck Reach: Specific Gauge Record for West Frazer Pump Plant, MT - RM 1751.3
	Figure_C5.xls	Fort Peck Reach: Specific Gauge Record for East Frazer Pump Plant, MT - RM 1736.6
	Figure_C6.xls	Fort Peck Reach: Specific Gauge Record for Oswego, MT - RM 1727.6
	Figure_C7.xls	Fort Peck Reach: Specific Gauge Record for the Missouri River near Wolf Point, MT - RM 1701.22
	Figure_C8.xls	Fort Peck Reach: Specific Gauge Record for Poplar River near Poplar, MT - RM 1678.9
	Figure_C9.xls	Fort Peck Reach: Specific Gauge Record for the Missouri River near Culbertson, MT - RM 1620.76
	Figure_C10.xls	Fort Peck Reach: Specific Gauge Record for Yellowstone River near Sidney, MT - RM 1582
Garrison	Figure_C11.xls	Garrison Reach: Specific Gauge Record for Stanton Gauge, ND - RM 1378.4
	Figure_C12.xls	Garrison Reach: Specific Gauge Record for Knife River near Hazen, ND - RM 1375.5
	Figure_C13.xls	Garrison Reach: Specific Gauge Record for Missouri River Near Fort Clark, ND - RM 1366.65
	Figure_C14.xls	Garrison Reach: Specific Gauge Record for Missouri River at Hensler Gauge, ND - RM 1362
	Figure_C15.xls	Garrison Reach: Specific Gauge Record for Washburn Gauge, ND - RM 1354.7
	Figure_C16.xls	Garrison Reach: Specific Gauge Record for Turtle Creek above Washburn, ND - RM 1351.9
	Figure_C17.xls	Garrison Reach: Specific Gauge Record for Price Gauge, ND - RM 1338
	Figure_C18.xls	Garrison Reach: Specific Gauge Record for the Missouri River at Bismark, ND - RM 1314.2
	Figure_C19.xls	Garrison Reach: Specific Gauge Record for Heart River near Mandan, ND - RM 1311.2

Directory	File Name	Contents
Fort_Randall	Figure_C20.xls	Fort Randall Reach: Fort Randall Dam Gauge, SD - RM 879.98
	Figure_C21.xls	Fort Randall Reach: Specific Gauge Record for Missouri River below Greenwood, SD - RM 865.04
	Figure_C22.xls	Fort Randall Reach: Specific Gauge Record for Misouri River Gauge at RM 853.37
	Figure_C23.xls	Fort Randall Reach: Specific Gauge Record for Ponca Creek near Verdel, NE - RM 848.9
	Figure_C24.xls	Fort Randall Reach: Specific Gauge Record for the Missouri River near Verdel, NE - RM 845.91
	Figure_C25.xls	Fort Randall Reach: Specific Gauge Record for the Niobrara River near Verdel, NE - RM 844
	Figure_C26.xls	Fort Randall Reach: Specific Gauge Record for the Missouri River near Niobrara, NE - RM 842.45
Gavins_Point	Figure_C27.xls	Gavins Point Reach: Specific Gauge Record for the Missouri River at Yankton, SD - RM 805.8
	Figure_C28.xls	Gavins Point Reach: Specific Gauge Relationship for James River at Yankton, SD - RM 800
	Figure_C29.xls	Gavins Point Reach: Specific Gauge Record for the Missouri River near Gayville, SD - RM 796
	Figure_C30.xls	Gavins Point Reach: Specific Gauge Record for the Missouri River near Maskell, NE - RM 775.8
	Figure_C31.xls	Gavins Point Reach: Specific Gauge Record for Vermillion River near Vermillion, SD - RM 772
	Figure_C32.xls	Gavins Point Reach: Specific Gauge Record for the Missouri River near Ponca, NE - RM 751

APPENDIX D: HEC-RAS ANALYSIS HYDRAULIC DATA FOR ALL FOUR REACHES

A complete set of tables generated from the HEC-RAS analysis is included in Appendix_D on the data supplement CD ROM that accompanies this report. These data were introduced in Section 4.5. Organization of Appendix_D is as follows:

Directory	File Name	Contents
Fort_Peck	D1_Fort_Peck_Data.xls	HEC-RAS analysis for Fort Peck Reach
Garrison	D2_Garrison_Data.xls	HEC-RAS analysis for Garrison Reach
	D3_Garrison_Data2.xls	HEC-RAS analysis for Garrison Reach (2)
Fort_Randall	D4_Fort_Randall_Data.xls	HEC-RAS analysis for Fort Randall Reach
	D5_Fort_Randall_Data2.xls	HEC-RAS analysis for Fort Randall Reach (2)
Gavins_Point	D6_Gavins_Point_Data.xls	HEC-RAS analysis for Gavins Point Reach

APPENDIX E: GRAIN SIZE PERCENTILE CURVES FOR ALL FOUR REACHES

The complete set of grain size percentile charts is shown in Appendix_E on the data supplement CD ROM that accompanies this report. These data were introduced in Section 4.6.2. Organization of Appendix_E is as follows:

Directory	File Name	Contents
Fort_Peck	E1_Fort_Peck_GS_Plots1.xls	Quantitative analysis of the grain size distributions of sediment samples for Fort Peck Reach (WPTs 148-255)
	E2_Fort_Peck_GS_Plots2.xls	Quantitative analysis of the grain size distributions of sediment samples for Fort Peck Reach (WPTs 256-312)
Garrison	E3_Garrison_GS_Plots.xls	Quantitative analysis of the grain size distributions of sediment samples for Garrison Reach
Fort_Randall	E4_Fort_Randall_GS_Plots.xls	Quantitative analysis of the grain size distributions of sediment samples for Fort Randall Reach
Gavins_Point	E5_Gavins_Point_GS_Plots.xls	Quantitative analysis of the grain size distributions of sediment samples for Gavins Point Reach

APPENDIX F: BRICE CLASSIFICATION DATA FOR ALL FOUR REACHES

A detailed description of the Brice Classifications for each of the four study reaches is shown in Appendix_F on the data supplement CD ROM that accompanies this report. These data were introduced in Section 4.9.3. Organization of Appendix_F is as follows:

File Name	Contents
F1_Brice_Classification.doc	A detailed description of the Brice classifications for each of the four reaches.

APPENDIX G: SEDIMENT BUDGET RESULTS FOR ALL FOUR REACHES

The results of the analysis using only the Pokrefke *et al.*'s (1998) data and those using the ERDC data are shown in Appendix_G on the data supplement CD ROM that accompanies this report. Appendix G also contains the sediment budget results calculated for varying bed material sizes ranging from 0.063 mm (the break between sands and silts) up to the actual bed material size selected for the reach. These data were introduced in Section 4.16. Organization of Appendix_G is as follows:

File Name	Contents
G1_ERDC_Budget.doc	'ERDC Budget' -- Results of the analysis using the ERDC data
G2_Pokrefke_Budget.doc	'Pokrefke Budget' -- Results of the analysis using the Pokrefke *et al.* (1998) data